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SMALL LAMINATED AXIAL TURBINE HOT-RIG TEST PROGRAM.(U)
JUL 78 R W VERSHURE, J C MAYS F33615-76-C-2176
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SMALL LAMINATED AXIAL TURBINE HOT-RIG TEST PROGRAM

R. W. VERSHURE, JR. AND J. C. MAYS

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
P.O. BOX 5217
PHOENIX, ARIZONA 85010

JULY 1978

INTERIM REPORT FOR PERIOD 15 SEPTEMBER 1976 - 28 FEBRUARY 1978

AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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In September, 1976, AiResearch Manufacturing Company of Arizona initiated a program for the United States Air Force Aero Propulsion Laboratory to hot-rig test TFE731-3 Axial Laminated Turbine Rotors and verify their heat-transfer performance and mechanical integrity. The testing was to be conducted in the AiResearch High Temperature Turbine Test Facility, and three major tests were planned - a heat-transfer over

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performance test, an accelerated stress-rupture test, and a thermal cyclic test. This interim report describes the progress to date on the Hot-Rig Program, just prior to the redirection in accordance with contract modification, P00003. This redirection concludes the Hot-Rig activities. The redirected test program will test one of the laminated turbine wheels directly in the Model 1131-1 Advanced Gas Generator. Also, a small laminated axial turbine rotor suitable for cruise missile application will be designed during this program.

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PREFACE

This interim report was submitted by AiResearch Manufacturing Company of Arizona, A division of The Garrett Corporation, under Contract F33615-76-C-2176. The effort was sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio under Project No. 3066, with Mr. Don Zabrierek, AFAPL/TBC, as Project Engineer. Mr. R. W. Vershure, Jr. of AiResearch was technically responsible for the work.

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SUMMARY

In September, 1976, AiResearch Manufacturing Company of Arizona initiated a program for the United States Air Force Aero Propulsion Laboratory to hot-rig test TFE731-3 Axial Laminated Turbine Rotors and verify their heat-transfer performance and mechanical integrity. The turbine rotors are being fabricated on the AFML Laminated Wheel Fabrication Development Program (Contract F33615-75-C-5211). The testing was to be conducted in the AiResearch High Temperature Turbine Test Facility, and three major tests were planned - a heat-transfer performance test, an accelerated stress-rupture test, and a thermal cyclic test. This interim report describes the progress to date on the Hot-Rig Program, just prior to the redirection in accordance with contract modification, P00003. In summary, the following major tasks were completed:

1) Heat-transfer calculations and predictions were completed to allow correlation of rig test performance to the design.

2) A hot-rig test plan matrix was established

3) Stress and life analyses were completed to assess the mechanical integrity in a hot dynamic environment. The stress rupture, based on a two-percent creep design curve at a rig inlet temperature of 2000°F, was calculated to be 700 hours.

4) Advanced instrumentation of the turbine rotating test rig was undertaken to allow measurement of pertinent temperatures, pressures, and airflows.

5) Rotating rig and facility modifications were undertaken to adapt to the planned test series and to add a radiation pyrometer blade metal temperature measurement capability in the dynamic test.

6) An in-process airflow check was performed on four Waspaloy laminated wheel blanks. Two of the wheel blanks are considered acceptable and are currently being finish machined.

The redirection concludes the Hot-Rig activities. The redirected test program will test one of the laminated turbine wheels directly in the Model 1131-1 Advanced Gas Generator. Also, a small laminated axial turbine rotor suitable for cruise missile application will be designed during this program.

SECTION I

INTRODUCTION

This document is submitted by the AiResearch Manufacturing Company of Arizona, a division of The Garrett Corporation, and presents the Interim Technical Report (DI-S-3591A) on "The Small Laminated Axial Turbine Hot-Rig Test Program", being conducted for the USAF Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio. The Program is authorized under Air Force Systems Command Contract No. F33615-76-C-2176, Project No. 3066. This interim report summarizes the axial turbine hot-rig design analysis and rig modification activity, which covers the period from September 15, 1976 to February 28, 1978.

The original objective of this program was to verify the heat-transfer performance and mechanical integrity of the laminated turbine wheel in a hot dynamic environment, and correlate the results with design predictions.

The testing was to be conducted in the AiResearch Company-Sponsored High-Temperature Turbine Test Facility, which was specifically developed to permit evaluation of cooled components for gas turbine engines. This facility, the advanced instrumentation, and associated equipment are described in Appendix A.

Four TFE731-3 Laminated Turbine Wheels were to be bailed to the test program from the AFML Laminated Wheel Fabrication Development Program (Contract F33615-75-C-5211). Two Waspaloy wheels were to be used in the airflow and component testing, and in the heat-transfer performance test in the high-temperature rotating rig. Two Astroloy wheels were to be used in the life tests, which are the accelerated stress rupture, and the thermal cycling tests in the hot rig.

In summary, the three major tests planned were:

1) A heat-transfer performance test to determine turbine blade and disk metal temperatures of the Waspaloy wheel over a range of turbine inlet temperatures, cooling airflow rates, and airflow temperature conditions.

2) An accelerated stress-rupture test of about 10 hours duration at steady-state conditions, using the Astroloy wheel, and testing to the limit of the rotors predicted two-percent creep life.

3) A thermal cyclic test to be conducted with the second Astroloy wheel. The thermal cycle will be accomplished by varying the mainstream gas temperature and periodically inspecting the rotor every 10 cycles, up to a total of 50 thermal cycles.

The following sections describe the progress to date on the Hot-Rig Test Program. This concludes the planned Hot-Rig Test activity to the point where the contract modification, P00003, redirected the effort to a small laminated axial turbine design and test program. The redirected test program will test the TFE731 laminated turbine wheel directly in an advanced gas generator engine environment, in place of the hot-rig testing.

SECTION II

DESIGN ANALYSIS

1. HEAT-TRANSFER PERFORMANCE PREDICTIONS

The expected metal temperature levels for the laminated Waspaloy turbine blade and disk were predicted based on the test conditions selected for the hot-rig and the test data obtained from the airflow bench testing of the turbine blades. In 1974, a Company-sponsored, high-temperature rotating rig was tested with the TFE731-3 high-pressure turbine rotor. The test results from this test became the basis for the planned hot-rig test with the 731 Laminated Turbine Rotor.

a. TFE731-3 Test Data Comparison

The Company-sponsored high-temperature rotating rig at AiResearch was utilized to test the first-stage turbine blades of the TFE731-3. During these tests, the rig was operated to an inlet temperature of 2057°F, an inlet pressure of 119.5 psia, a main flow of 18.4 lb/sec, a speed of 30,223 rpm, and a power level of 1378 hp. A total of fourteen test points was obtained. For each point, all pertinent parameters were measured, including a radiation pyrometer metal temperature scan of all the blades on the rotor. A schematic of the test section is shown in Figure 1, including the instrumentation and pyrometer installation. Figure 2 shows a typical set of data. These results were considered in establishing heat-transfer performance predictions for the laminated turbine blade.

b. Heat-Transfer Verification Test

The overall objective of this program is to verify the heat-transfer performance of the laminated turbine wheel in a hot, dynamic environment; and to correlate the results with

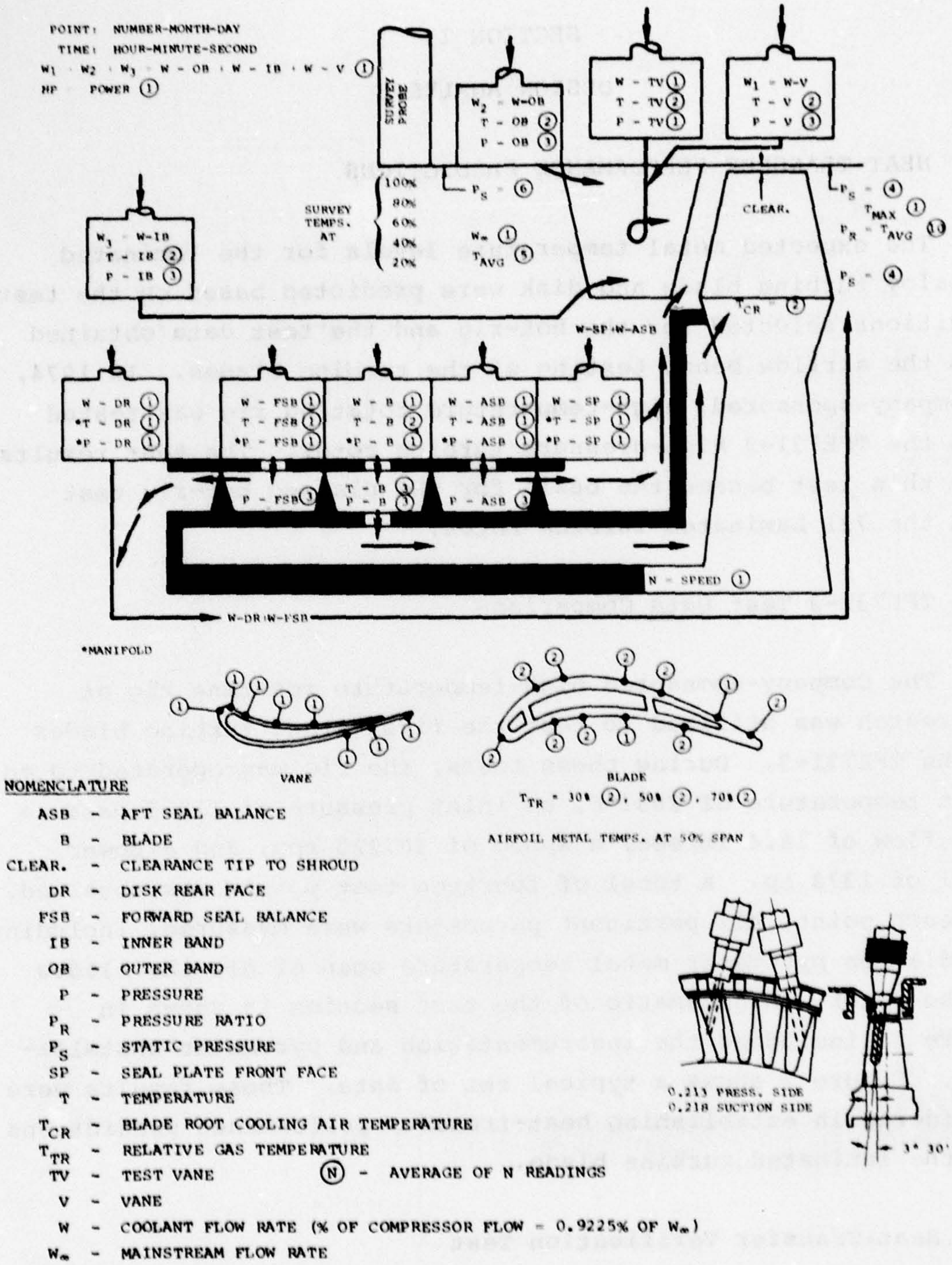


Figure 1. Test Section Schematic for TFE731-3.

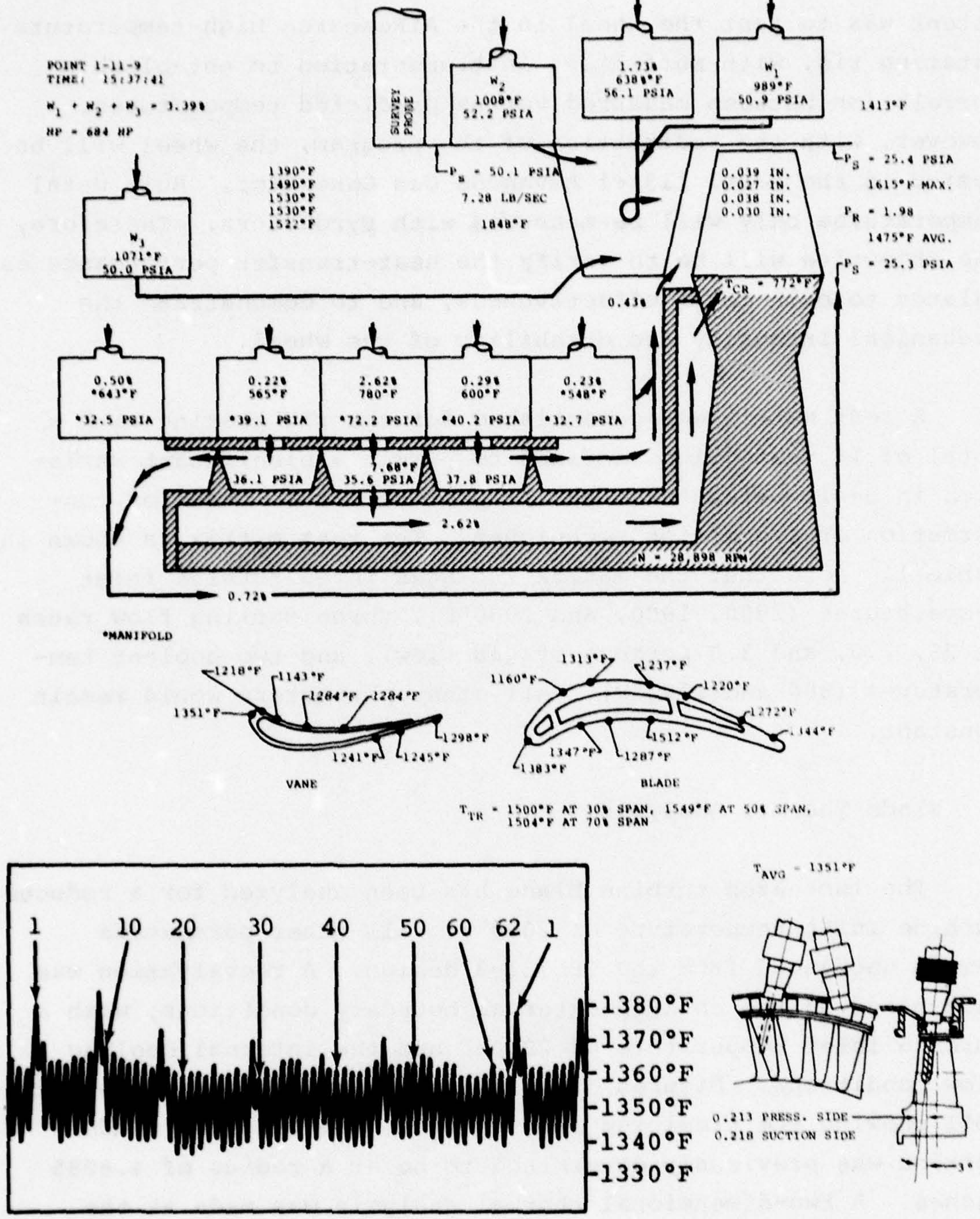


Figure 2. Typical Test Results from TFE731-3.

design predictions. To accomplish this objective, the original intent was to test the wheel in the AiResearch high-temperature rotating rig, with sufficient instrumentation to establish a correlation between measured versus predicted temperatures. However, with the redirection of the program, the wheel will be tested in the Model 1131-1 Advanced Gas Generator. Bulk metal temperatures only will be measured with pyrometers. Therefore, the objective will be to verify the heat-transfer performance as related to bulk metal effectiveness, and to demonstrate the mechanical integrity and durability of the wheel.

A test matrix was established for the rig testing with a total of 18 test points defined to permit a significant variation in basic parameters, and to provide a data base for confirmation of prediction techniques. The test matrix is shown in Table 1. Note that the matrix includes three turbine inlet temperatures (1800, 1900, and 2000°F), three cooling flow rates (1.25, 2.0, and 3.0 percent of gas flow), and two coolant temperatures (800 and 1000°F). All other parameters would remain constant.

c. Blade Thermal Analysis

The laminated turbine blade has been analyzed for a reduced turbine inlet temperature of 2000°F. All other parameters remain unchanged from the TFE731-3 design. A reevaluation was made based on the changed external boundary conditions, with a turbine inlet temperature of 2000°F and the internal cooling flow conditions. Figures 3 and 4 are cross sections of the airfoil showing the predicted flow splits. The critical blade section was previously determined to be at a radius of 4.6095 inches. A two-dimensional thermal analysis was made at the critical section to determine metal temperatures under combined effects of convection and conduction. Figure 5 shows the element and nodal layout of the critical section grid model. The outside heat-transfer coefficients and adiabatic wall

TABLE 1. TEST MATRIX FOR THE HEAT-TRANSFER VERIFICATION TEST IN THE HIGH-TEMPERATURE TURBINE RIG.

T_{gas} (°F)	Cooling Flow (% W_{gas})	Cooling Air Temp (°F)
1800	8.0	800
	6.0	
	4.0	
	8.0	1000
	6.0	
	4.0	
1900	8.0	800
	6.0	
	4.0	
	8.0	1000
	6.0	
	4.0	
2000	8.0	800
	6.0	
	4.0	
	8.0	1000
	6.0	
	4.0	

All other parameters to remain constant.

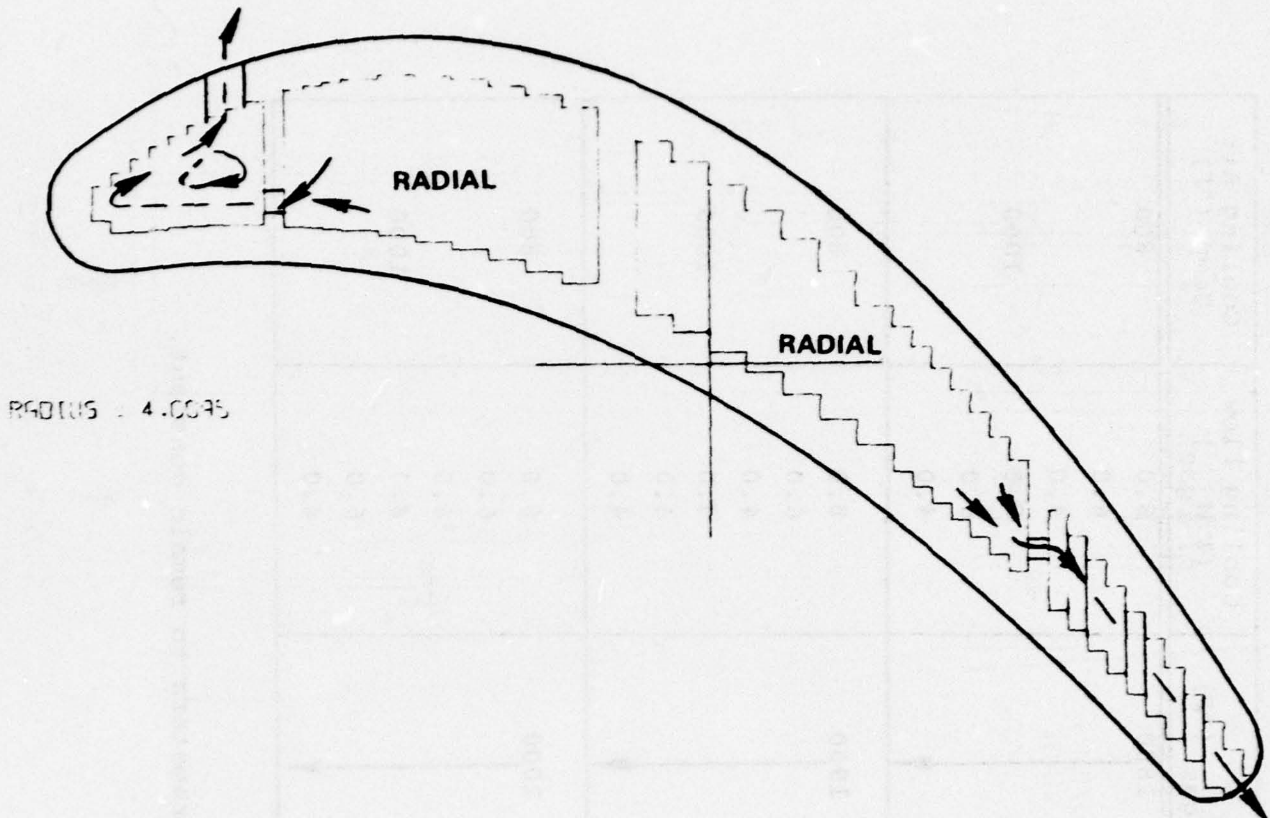
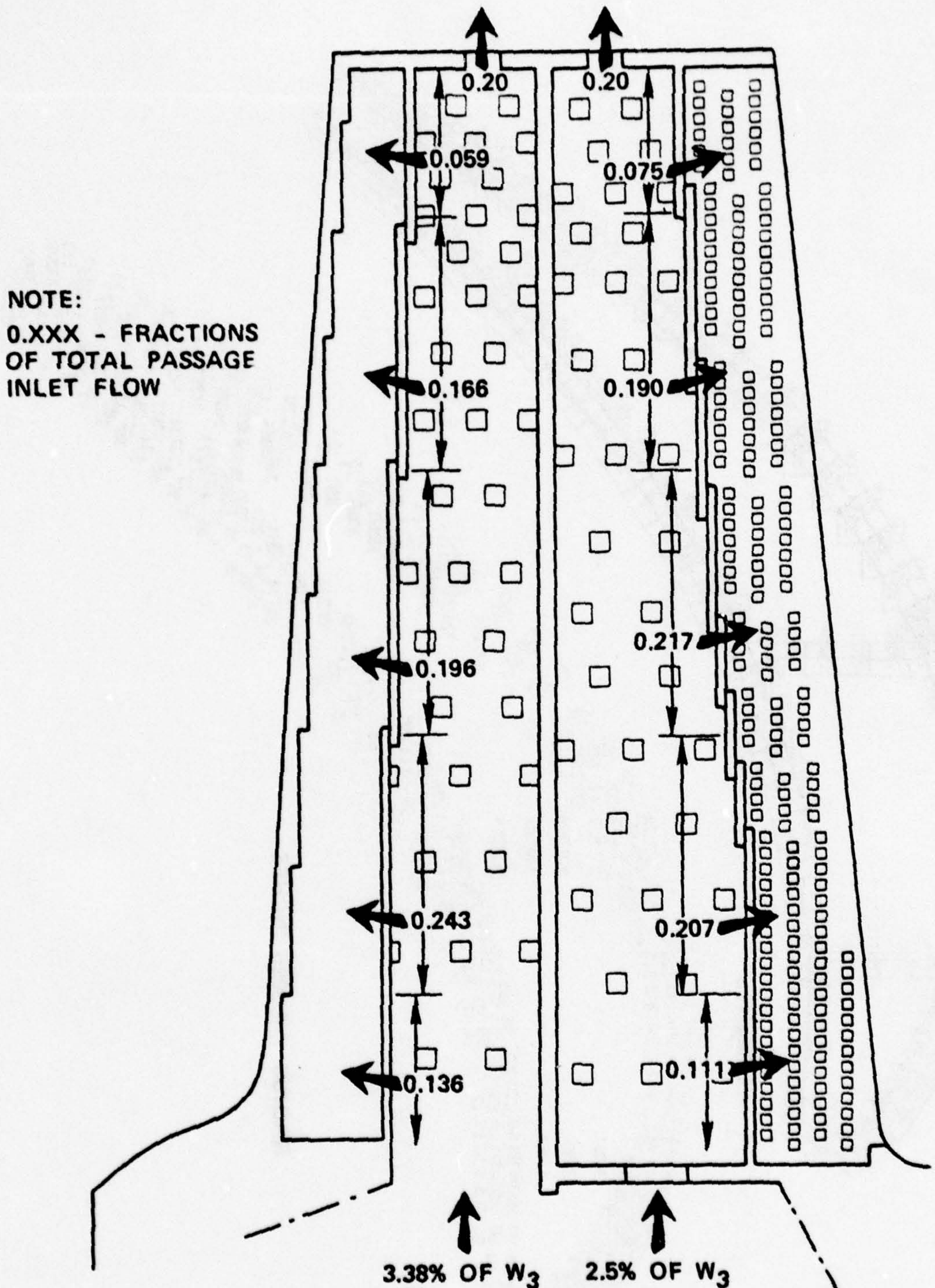


Figure 3. Laminated Blade Chordwise Flow Patterns.



TOTAL COOLANT FLOW = 5.88 PERCENT OF COMPRESSOR FLOW (W_3)

Figure 4. Laminated Blade Cooling-Flow Split and Radial Distribution.

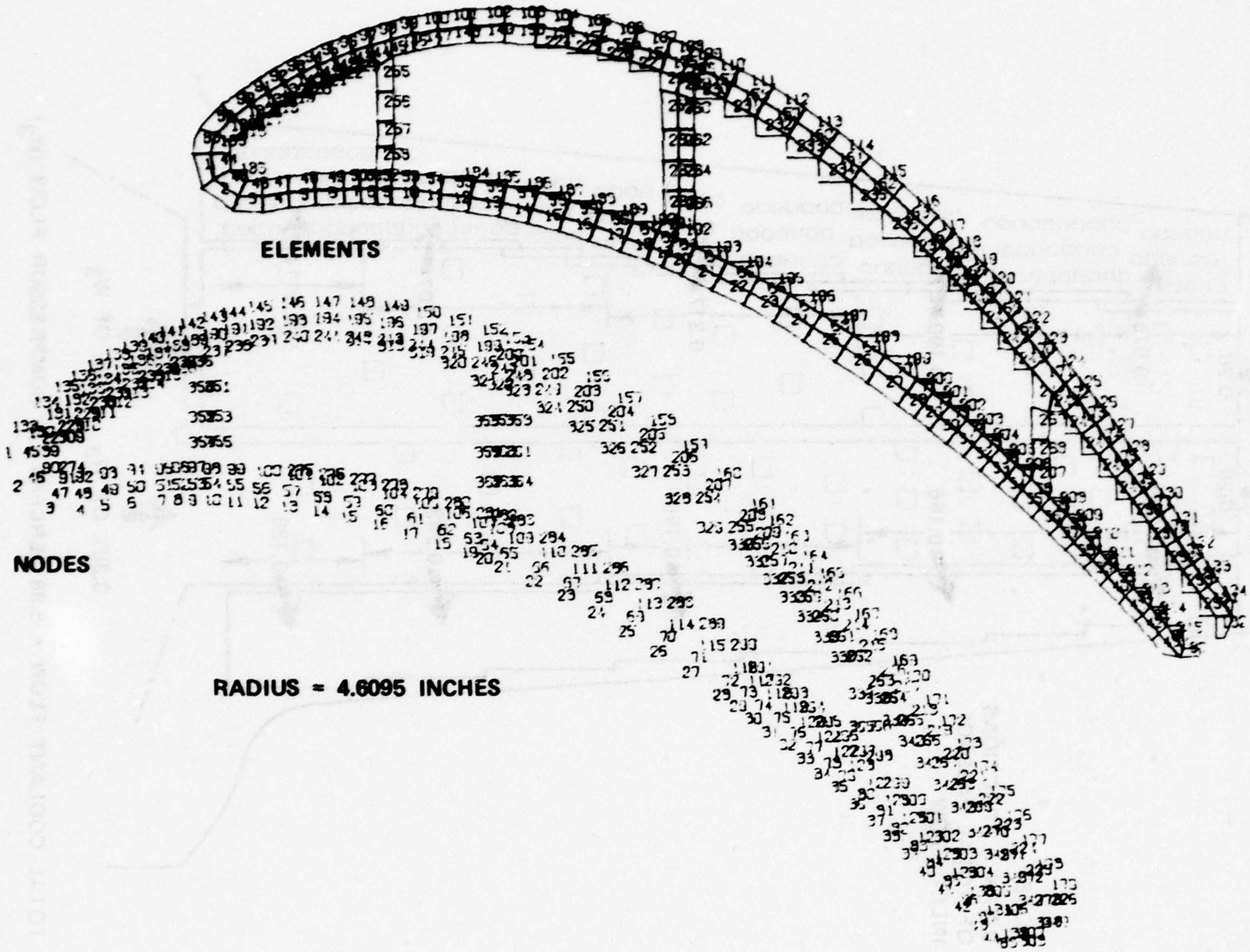


Figure 5. Laminated Turbine Blade Critical Section Grid Model.

temperatures are shown in Figures 6 and 7, respectively. The resulting steady-state metal temperatures are shown in Figure 8. These temperatures were then used in the stress and life analyses described below.

d. Stress and Life Analyses

1) Laminated Waspaloy-A Creep Properties - A two-percent creep design curve for the laminated turbine of Waspaloy-A was developed from AiResearch test data and from consideration of the parent material stress-rupture properties. This curve is shown in Figure 9.

2) Blade Stress Analysis - The steady-state stress solution for the critical solution was computed with the completion of the two-dimensional thermal analysis of the blade critical section, and the calculated radial load and moments acting on this section due to gas-bending loads and centrifugal loading. This program combines thermal stresses and mechanically generated stresses to describe a steady-state, two-dimensional, uniaxial stress field. This solution for an average TIT of 2000°F and with a 5.9 percent cooling flow is shown in Figure 10.

   In addition to the steady-state stress calculation, a creep analysis of the blade was also performed. The critical section creep behavior occurs over a finite radial length of the blade. The blade stress distribution is recalculated after each increment of creep strain, using the steady-state temperature distribution. Calculated creep strains and stress values are continued until some element in the blade reaches the creep-strain limit of two percent.

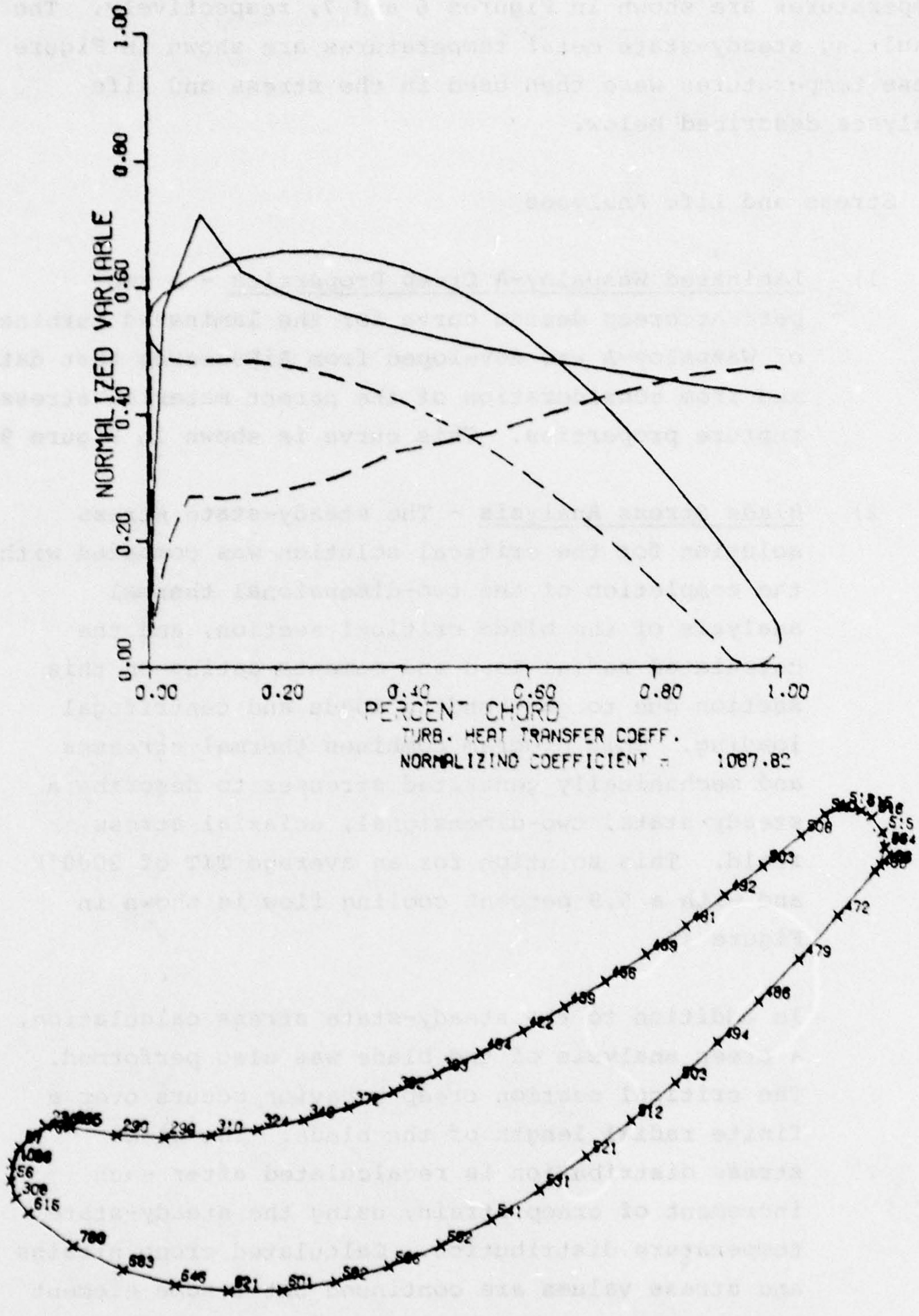


Figure 6. Laminated Turbine Blade Outside Heat Transfer Coefficients at 2000°F T.I.T.

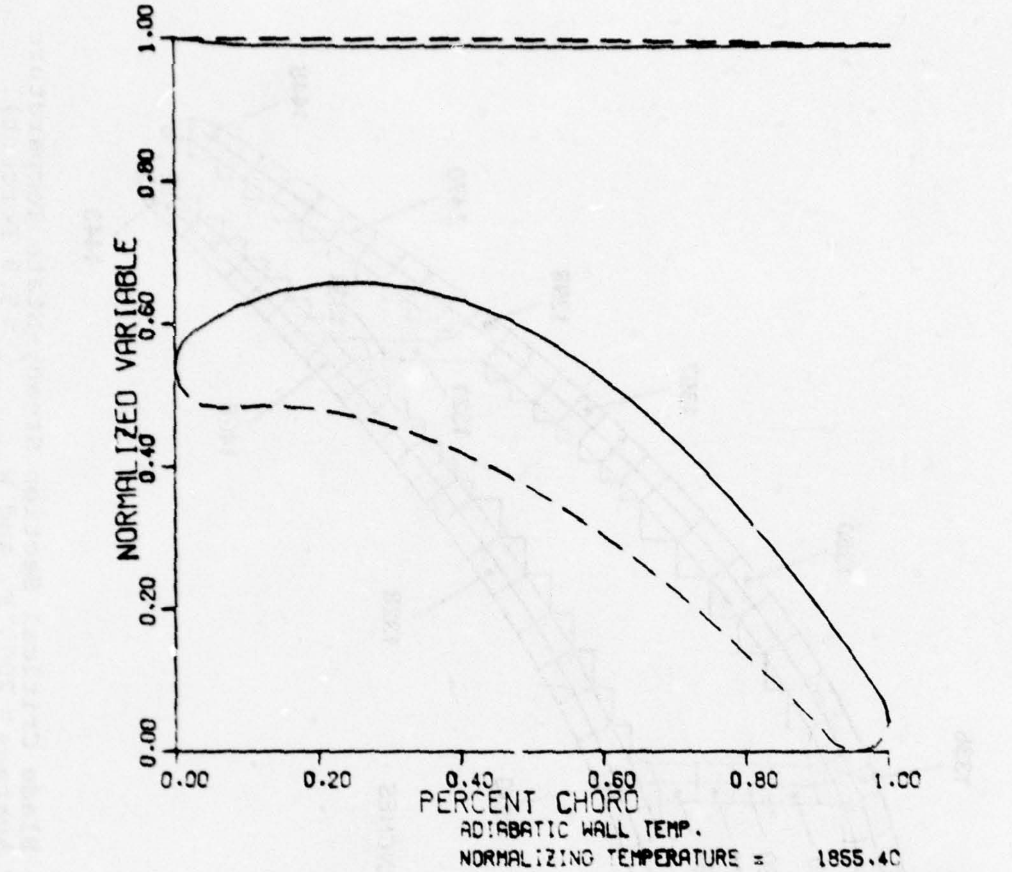


Figure 7. Laminated Turbine Blade Adiabatic Wall Temperatures at 2000°F T.I.T.

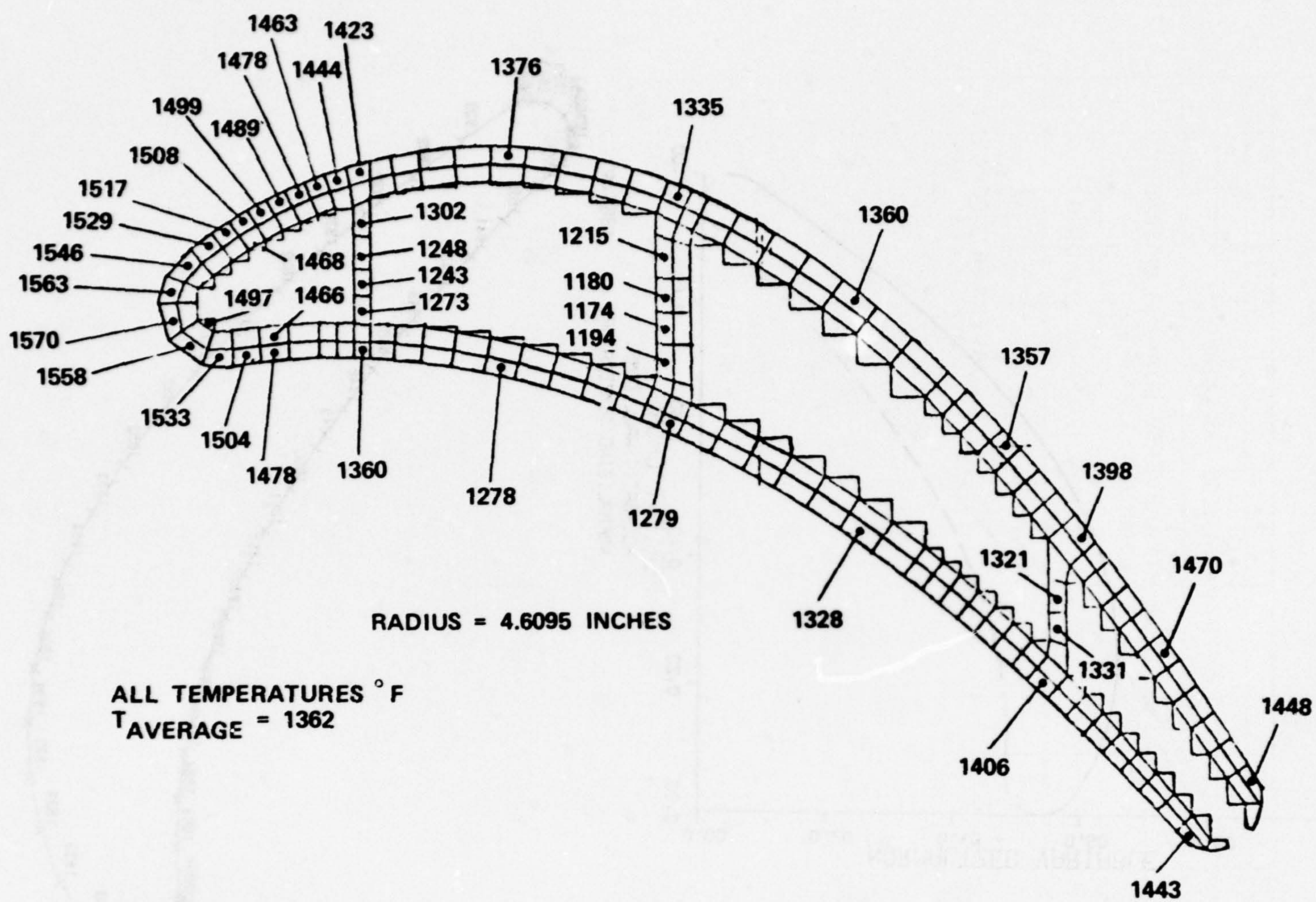
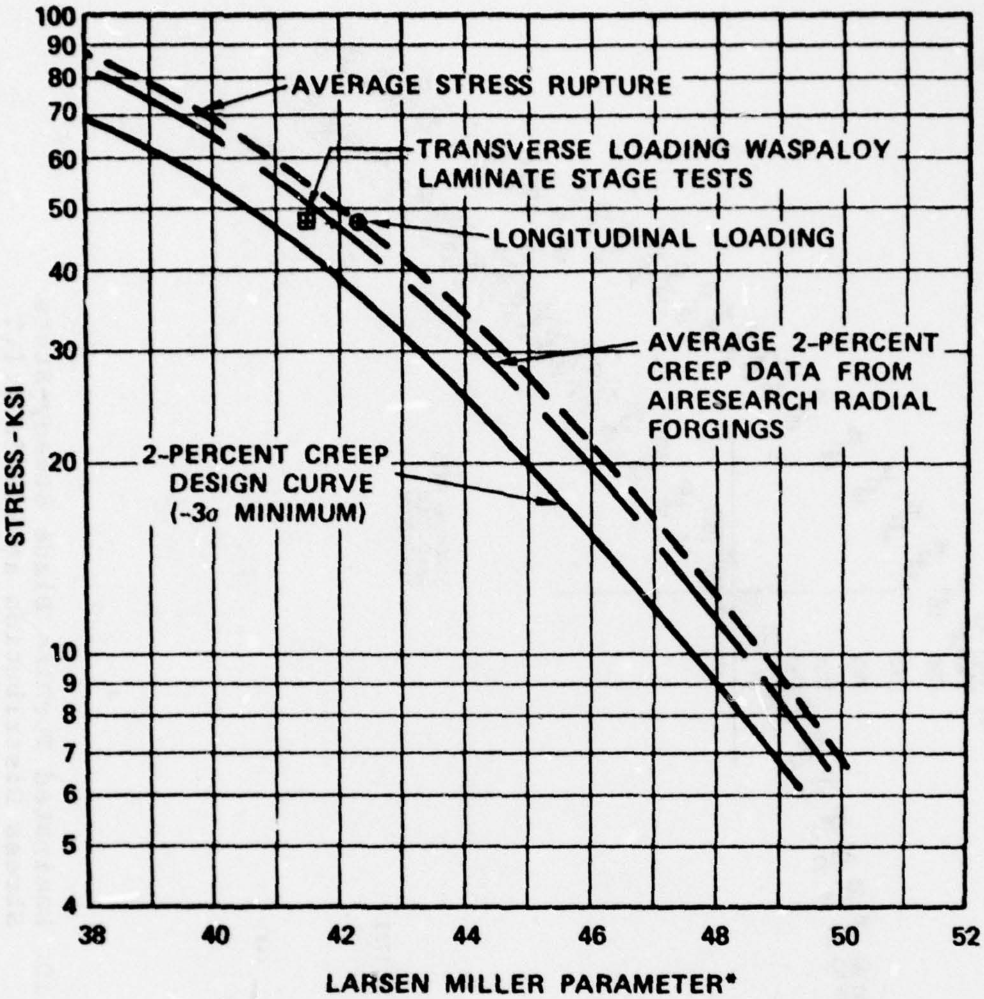


Figure 8. Laminated Turbine Blade Critical Section Steady-State Temperature Distribution (TIT Average = 2000°F, and $W_{coolant}$ = 5.9 Percent).



*$LMP = (T+460)(20 \ LOG_{10}t)(10^{-3})$

Figure 9. Laminate Waspaloy-A 2-Percent Creep Design Curve.

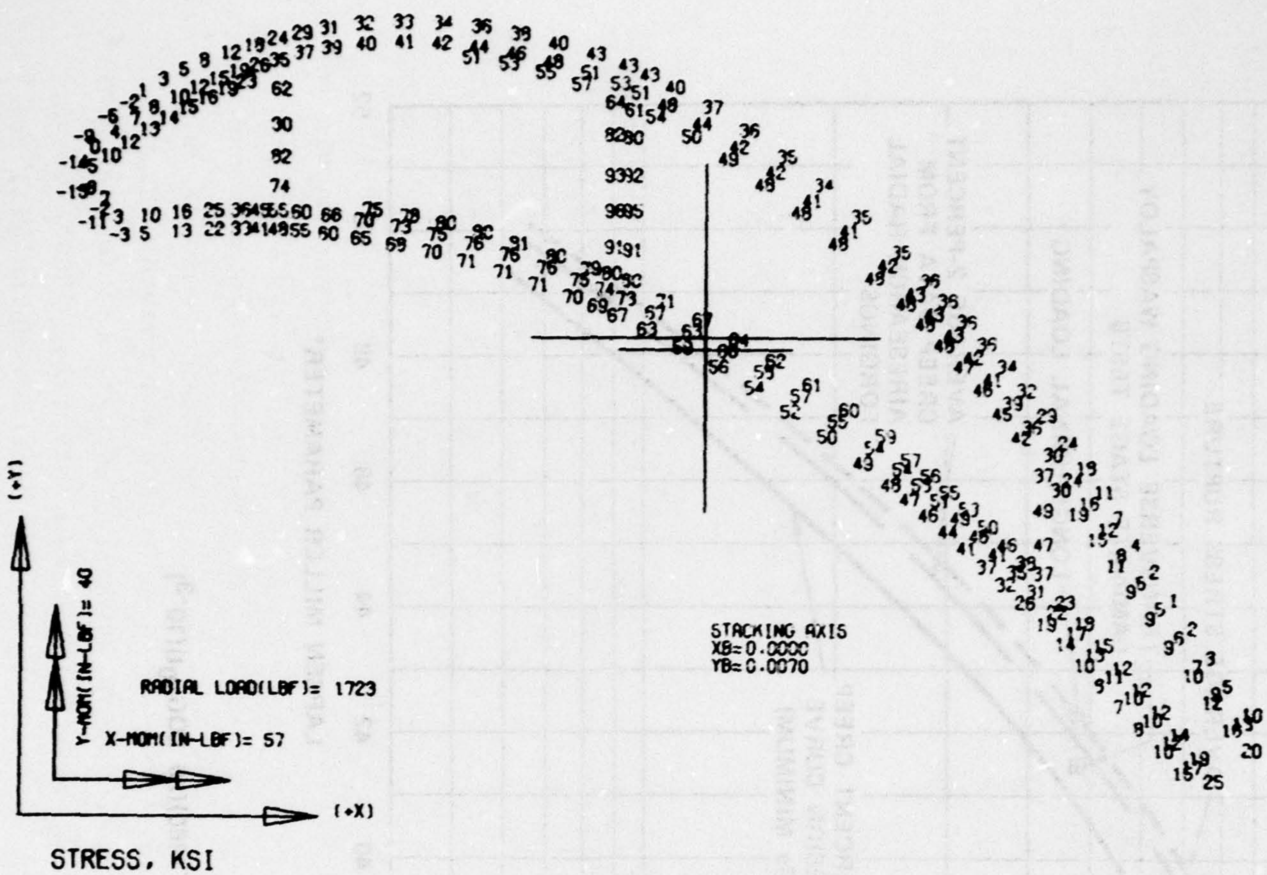


Figure 10. Laminated Turbine Blade Steady-State Stress Distribution at 2000°F T.I.T.

The two-percent creep life at an average TIT of 2000°F, with a 5.9 percent cooling flow, using calculated metal temperature, is 700 hours. The failure or maximum strain location is along the suction wall of the forward center cavity. The creep distribution at 700 hours is shown in Figure 11. The stress distribution at 700 hours is also shown in Figure 12. The peak steady-state tensile stress in the center-passage divider has fallen from 96 ksi to 72 ksi, and the creep strain at this location is 1.6 percent. The leading-edge compressive stress has become tensile due to strain relief during the initial creep period, and the creep strain at 700 hours is 1.4 percent. The creep strains for compression and tension are added algebraically to determine a final value. In general, the high tensile stresses along the pressure wall at mid-chord have decreased substantially at 700 hours; and on the suction wall, the outer-fiber stresses have increased slightly, as shown in Figures 10 and 12.

3) <u>Disk Stress Analysis</u> - Previously conducted stress analysis of the fully bladed rotor as reported in AFAPL-TR-77-2 indicated the adequacy and margin for use of this design in room-temperature whirlpit testing. Installation of the rotor in a demonstrator engine and operation at the design speed of 29,692 rpm will result in increased stresses at the bore and rim, due to thermal gradients in the disk. The anticipated thermal gradients for a 2000°F TIT and normal secondary cooling of the turbine will not be severe, and although the resulting increase in stresses will reduce the LCF life of the component, its integrity for a short-term demonstration test should not be affected. If long-term cyclic testing

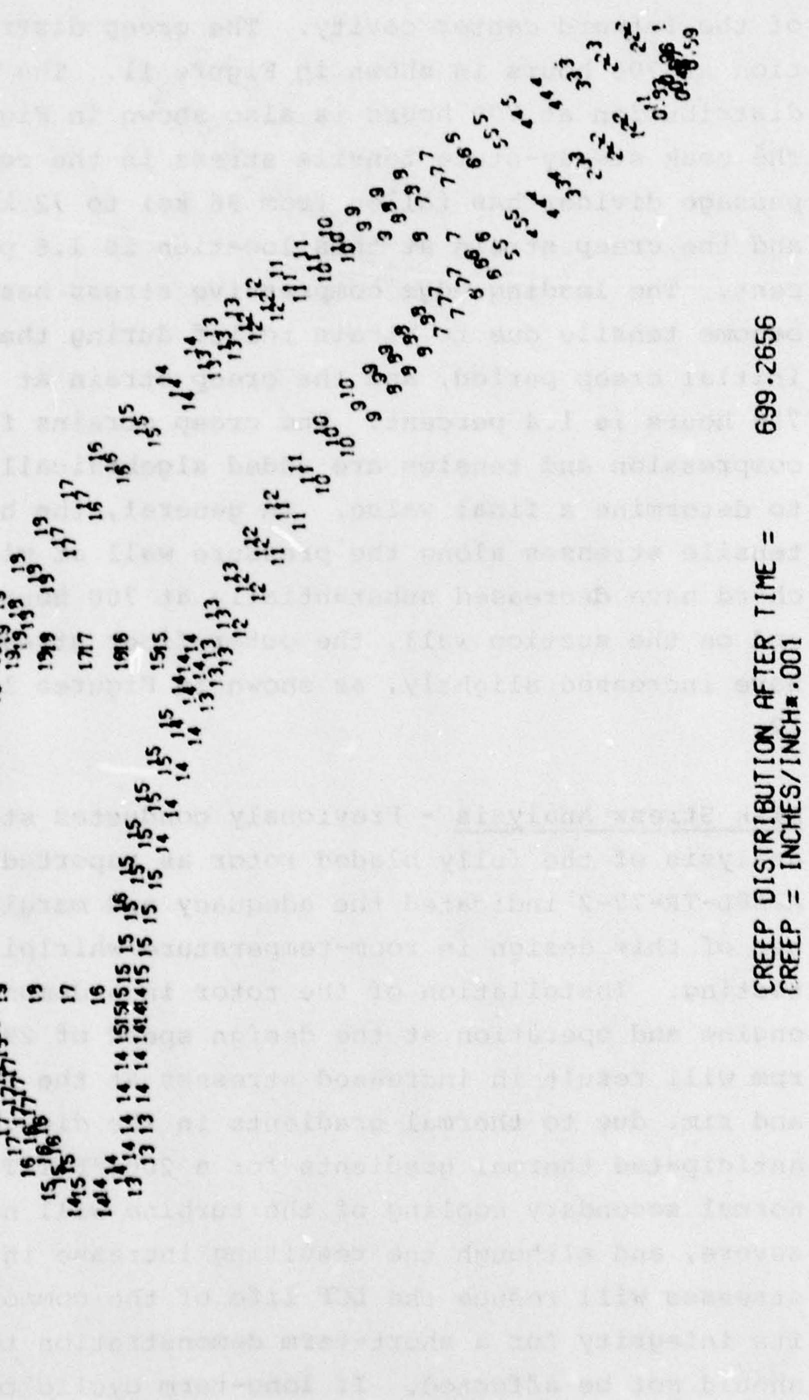


Figure 11. Laminated Turbine Blade (T.I.T. = 2000°F).

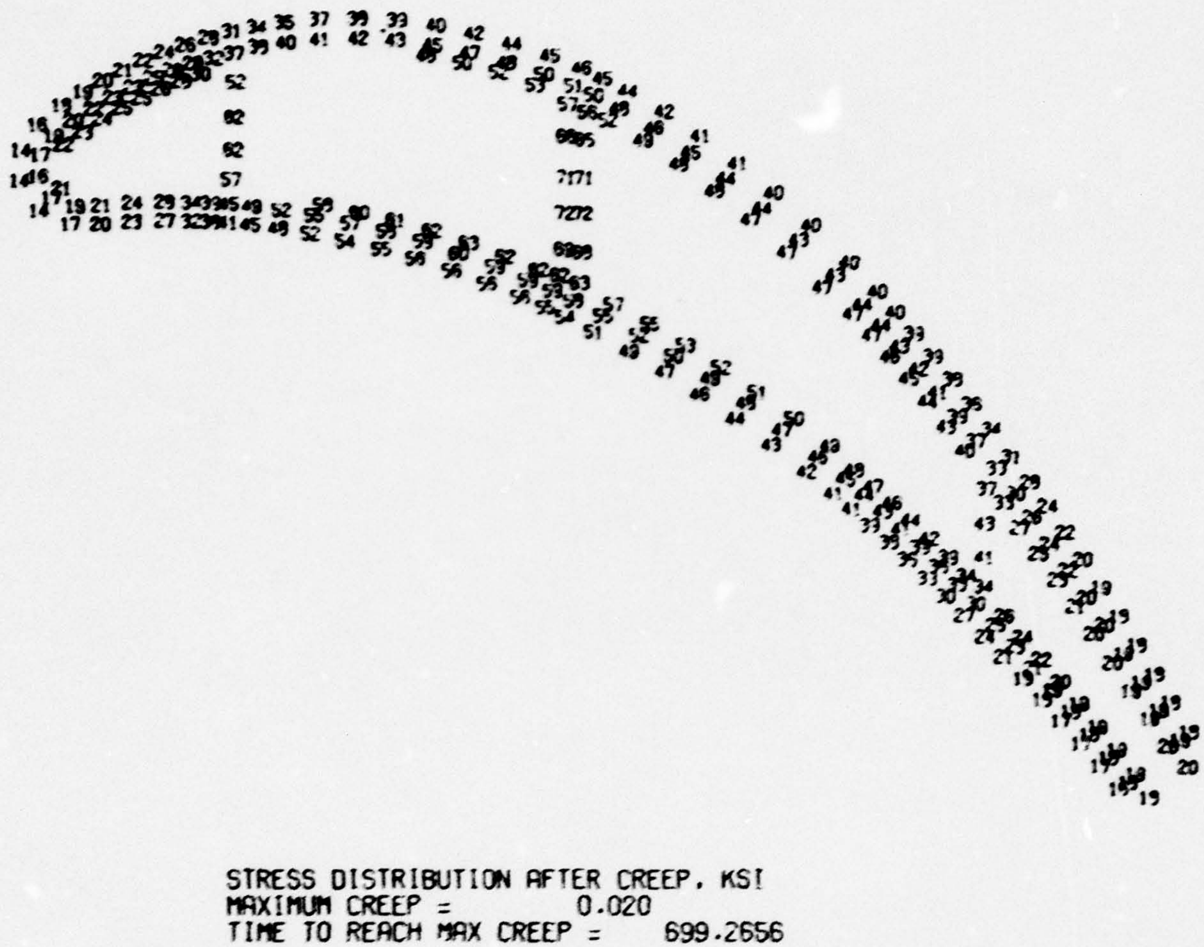


Figure 12. Laminated Turbine Blade (T.I.T. = 2000°F)

in an engine environment is to be considered in the future, a more detailed examination of fatigue life would be required.

SECTION III

ADVANCED INSTRUMENTATION

The instrumentation of the high-temperature turbine rotating test rig was undertaken to allow measurement of all cooling airflows, pressures, and temperatures, inlet and exhaust hot gas pressures and temperatures, turbine tip clearance, and critical static component metal temperatures. A detailed description of the instrumentation, readout devices, and data acquisition equipment is included in Appendix A.

To measure the laminated turbine blade metal temperatures, two methods were to be utilized:

1) Thermocouples were to be placed in grooves in the blade surface and flame sprayed in place to obtain a smooth aerodynamic surface.

2) A radiation pyrometer was to be installed in the rig to allow measurement of blade-to-blade metal temperature variations, to determine uniformity of cooling.

A review of the laminated turbine blade thermocouple installation was accomplished using the first APL rotor as shown in Figure 13. The following conclusions were reached:

1) The plasma-spray method of installation is limited to the leading-edge and the trailing-edge regions (1/3 chord) of the blade.

2) The center section of the blade cannot be plasma sprayed because the spray angle is too great to obtain an effective bond joint. However, it is

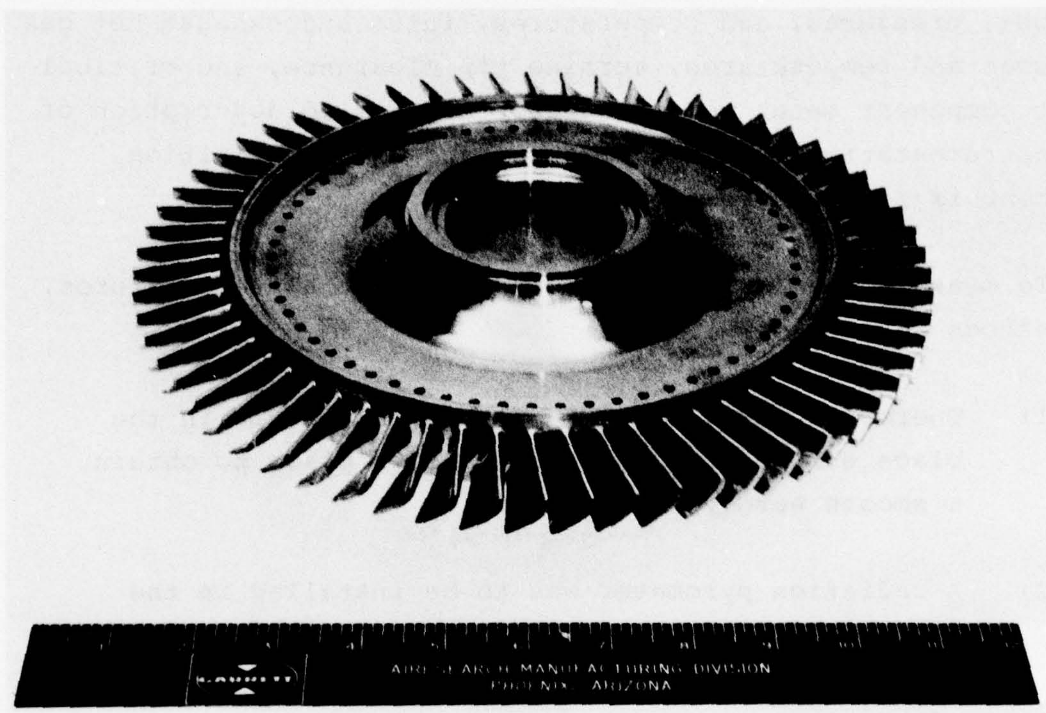
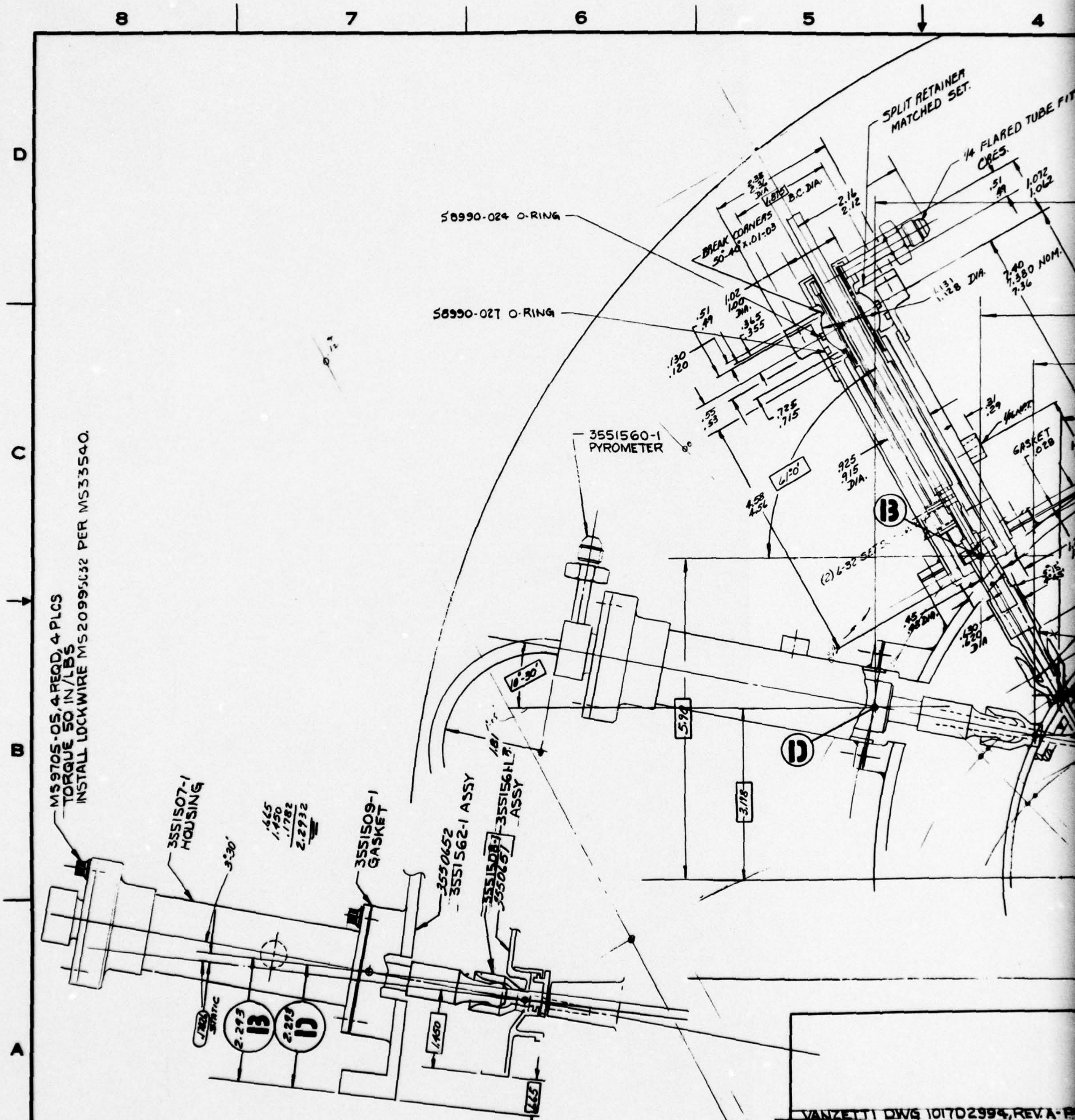


Figure 13. APL Turbine Rotor.

believed possible to install calibration thermocouples using furnace brazing techniques. This would provide a reference temperature to compare to the radiation pyrometer measurement.

The radiation pyrometer installation was modified to correct for a bellows distortion problem noted on the previous TFE731-3 hot rig testing. The new pyrometer installation is shown in Figure 14. This new approach utilizes a double spherical seat for locating and air sealing the probe in the two housings, thereby eliminating the bellows assembly. Two probes of the new design were to be installed to measure the blade suction- and pressure-side metal temperatures. The pyrometer, as shown in Figure 15, manufactured by Vanzetti Corp., has a higher frequency response than the previous pyrometer used in the initial testing (150 KHz versus 40 KHz). The higher frequency response ensures recording of the highest blade metal temperature during the short time period of viewing each blade. The Vanzetti pyrometer and the associated electronic signal conditioning equipment was tested successfully at AiResearch on the STAGG Gas Generator Test Program.



SPLIT RETAINER MATCHED SET.
1/4 FLARED TUBE FITT...
58990-024 O-RING
58990-027 O-RING
BREAK CORNERS
B.C. DIA.
3551560-1 PYROMETER
GASKET
(2) 6-32 SETS
MS9705-05, 4 REQD, 4 PLCS
TORQUE 50 IN/LBS
INSTALL LOCKWIRE MS20995C32 PER MS33540.
3551507-1 HOUSING
3551509-1 GASKET
3550652
3551562-1 ASSY
3551508-1
3550651
3551561-1 ASSY
STATIC
VANZETTI DWG 1017D2994, REV. A-...
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REF DWGS:
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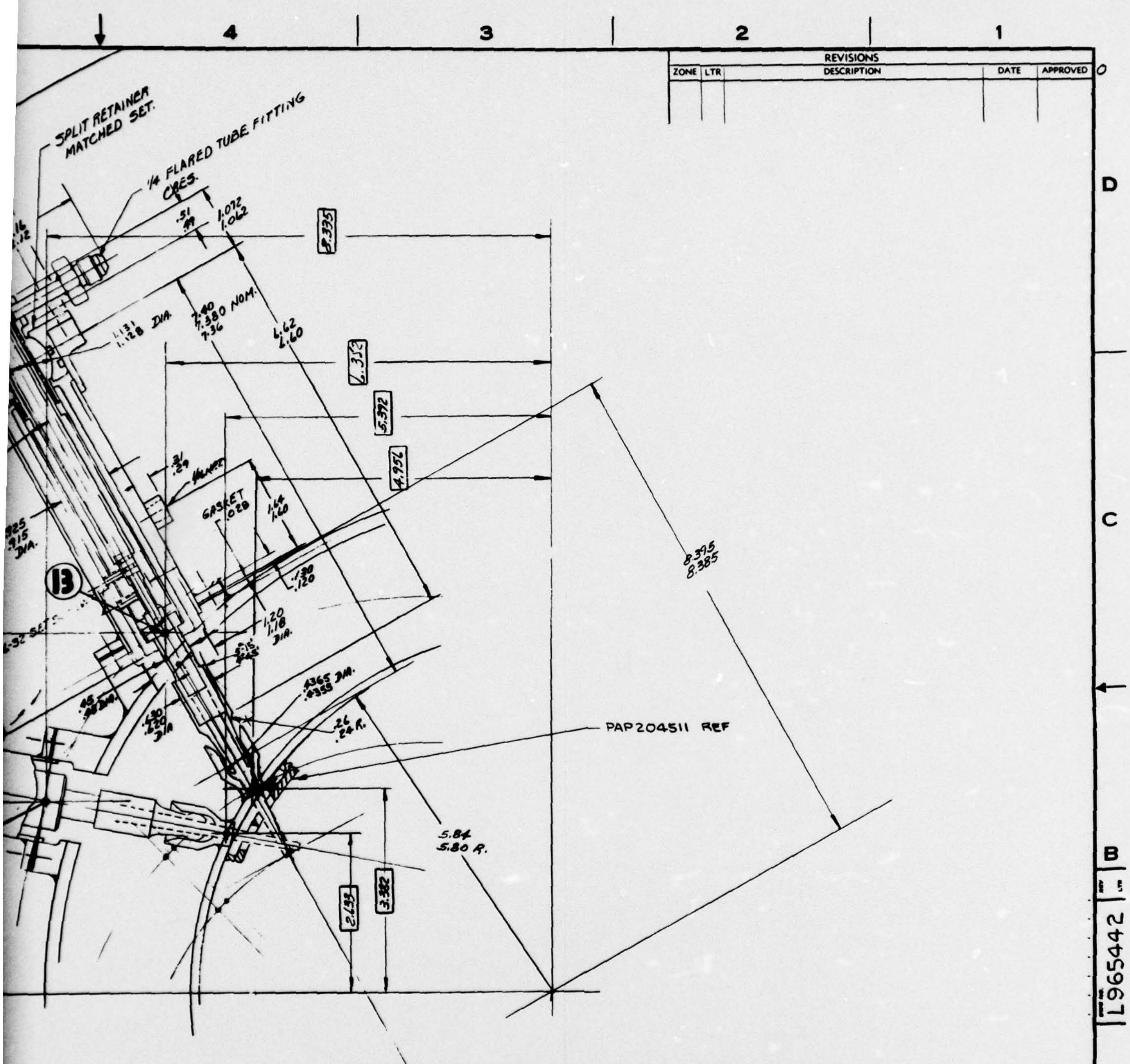

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PARTS LIST

...ETTI DWG 1017D2994, REV. A - PROBE ASSY.
...0640 - HOT TURBINE RIG.
...005 - PYROMETER INSTALLATION
...ES:

REQD	NEXT ASSY	USED ON
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DWG TITLE
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OPTICAL TEMPERATURE SENSOR

SIZE	CODE IDENT NO.	DWG NO.
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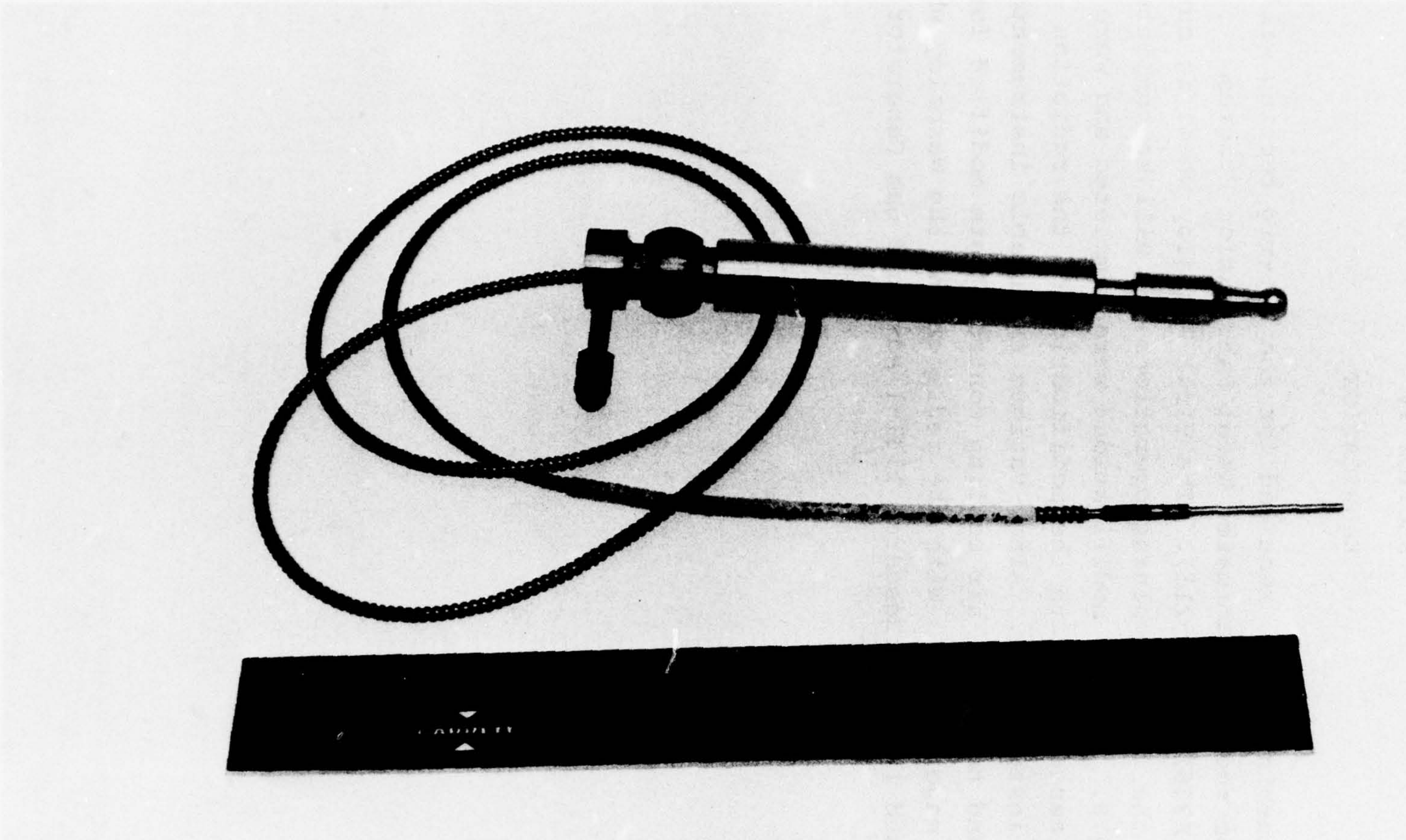


Figure 15. Pyrometer Manufactured by Vanzetti Corporation.

SECTION IV

FABRICATION

The turbine wheels required for the hot-rig testing will be bailed from the AFML Laminated Wheel Fabrication Program (Contract F33615-75-C-5211). The first Waspaloy wheel is currently in the final machining operations and will be completed in July 1978. The rig modifications were completed and were primarily associated with the modification of the radiation pyrometer installation. Also, various expendable instrumentation hardware and test cell air cooling controls were modified for the three major tests. With the redirection, the Waspaloy wheel will be used in the AiResearch 1131-1 Advanced Gas Generator Test.

SECTION V

AIRFLOW TESTING

An in-process airflow check was performed on the four Waspaloy laminated wheel blanks that were fabricated in the AFML Laminate Wheel Fabrication Program. At this point in the process, the only cooling-flow circuits open are the blade tip discharge holes. Each of these 62 circuits was checked individually by applying 30 in. Hg pressure to their respective inlets on the face of the disk. It should be noted, however, that the flow through these circuits is metered at the tip holes. Therefore, the flow check is significant in only three respects:

1) It verifies that the cooling passages are open.

2) It measures the flow characteristics and repeatability of the tip discharge holes.

3) It checks for leakage from each cooling circuit or cross flow between cooling circuits.

The results of the airflow testing are shown in Figures 16 and 17. Figure 16 presents the flow distribution of each hole. It also shows the deviation from the mean value for Serial Nos. 001 and 002 wheel blanks of 0.00259 pps. Figure 17 presents the median rank plot on normal probability distribution paper. Note that for the Serial Nos. 001 and 002 wheel blanks, 72 percent of the passages are within 5 percent of the mean, and 98 percent are within 10 percent of the mean. However, Serial No. 003 exhibited a substantial improvement in flow distribution, having 100 percent of the holes within 3 percent of the mean. This improvement was attributed to a modification of the bonding tooling, which provided a more uniform unit load distribution across the wheel blank. This airflow distribution compares favorably to a cast inserted blade configuration, which is allowed ±10 percent variation from the mean.

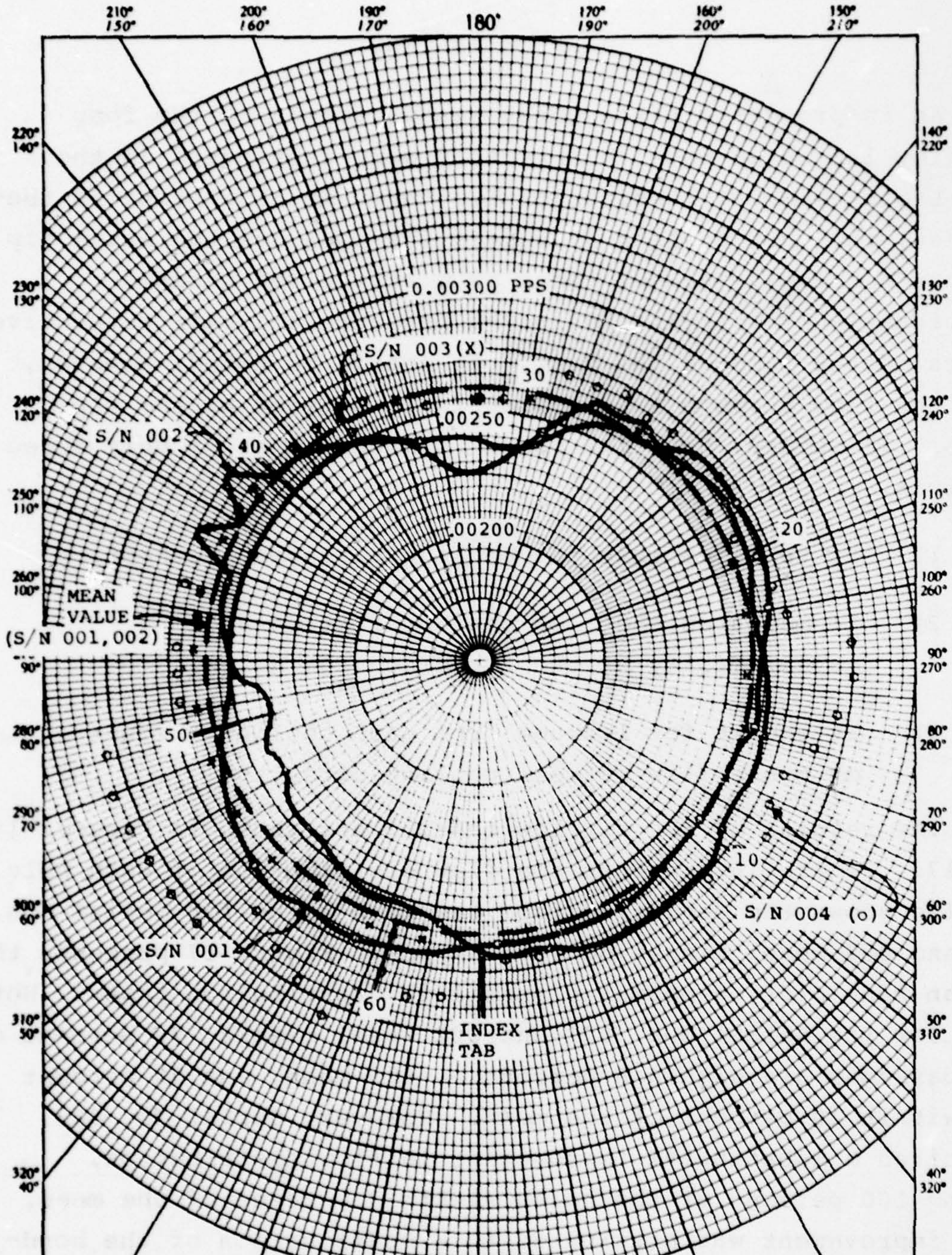


Figure 16. In-Process Flow Check of Laminated Rotor for the Small Axial Laminated Turbine Program (Before Machining).

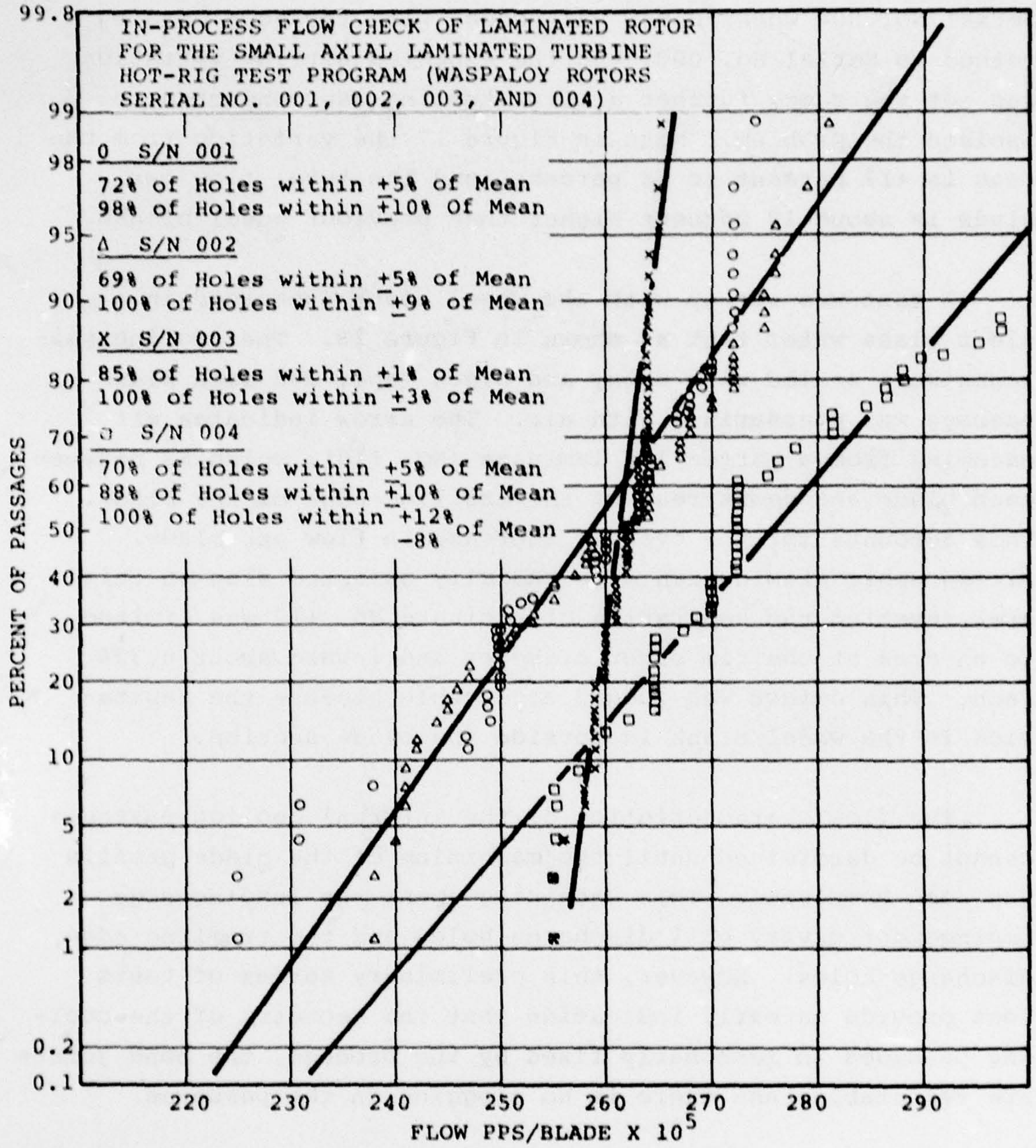


Figure 17. Flow Variation of Cooling Passages, Median Rank Plot.

The airflow check of Serial No. 004 wheel blank uncovered a secondary leakage problem in this particular part. Since the Serial No. 004 wheel blank was bonded with the same bonding method as Serial No. 003, and the expected airflow variation was not the same, further airflow testing was conducted to isolate the problem. Note in Figure 17 the variation from the mean is +12 percent to -8 percent, and the total flow per blade is about 10 percent higher than previous wheel blanks.

A test was set up with the wheel blank submerged in a clear glass water tank as shown in Figure 18. The cooling passages were sealed with epoxy and black tape, and each blade passage was pressurized with air. The arrow indicates air escaping from a particular laminate (No. +19), which is between each blade and downstream of the trailing-edge of the blade. This accounts for the overall increase in flow per blade. Micrographic examination of a radially oriented slug in this area revealed the separation of Laminate No. +19 was limited to an area at the rim outer diameter and inward about 0.320 inch. This defect was judged acceptable because the separation in the wheel blank is outside the blade section.

The flow characteristics of the internal cooling passages cannot be determined until the machining of the blade profile has been completed. This machining opens the leading-edge impingement cavity gill discharge holes and the trailing-edge discharge holes. However, this preliminary series of tests does provide an early indication that the geometry of the cooling passages is reasonably fixed by the process, the bond joints are repeatable, and there is no clogging in the passages.

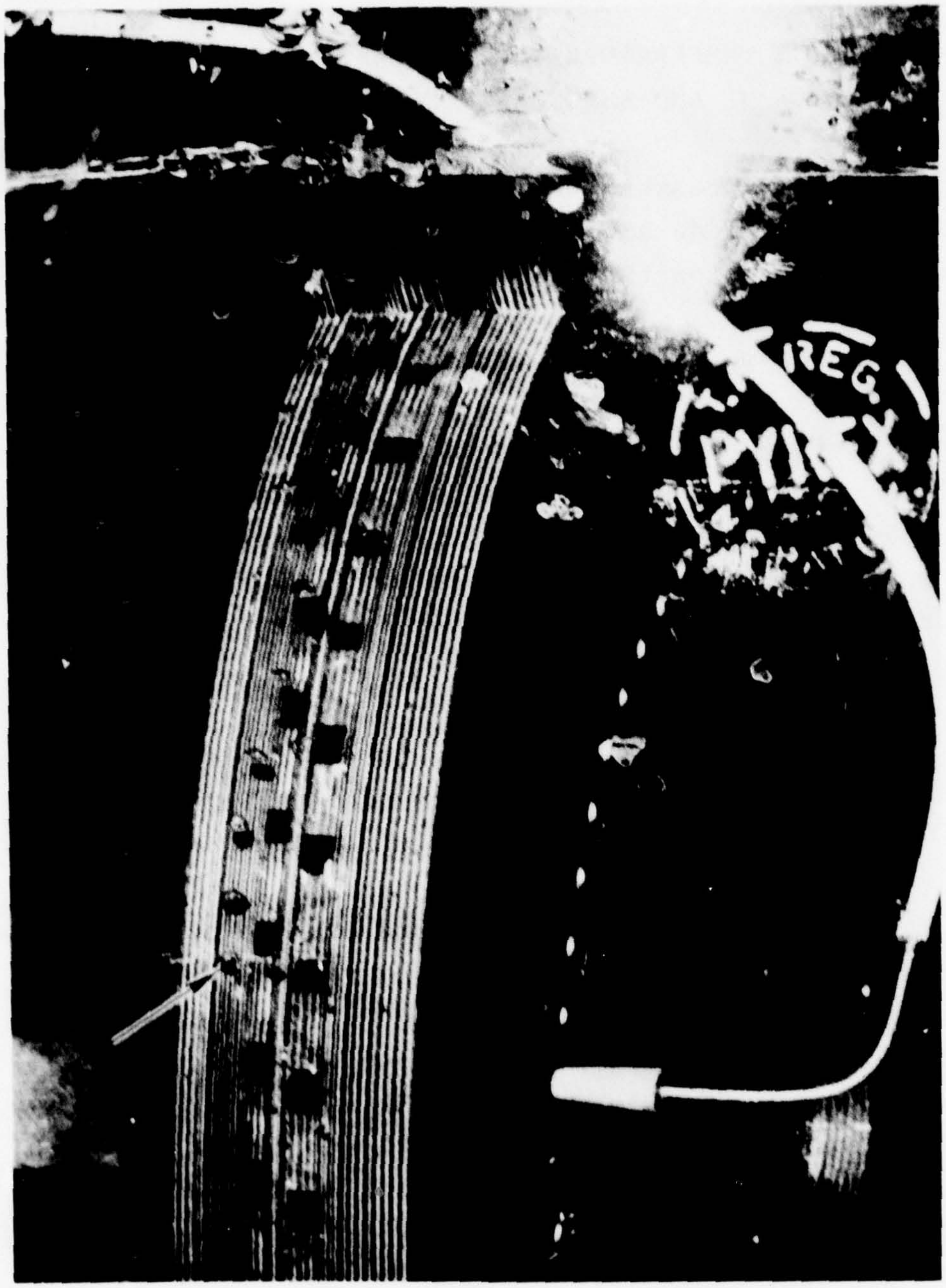


Figure 18. In-Process Air Leakage Check of Laminated Wheel Blank, Serial No. 4. (Arrow Indicates Leakage at Laminate No. +19 Between Blades.)

APPENDIX A

HIGH TEMPERATURE TURBINE TEST FACILITIES AND ASSOCIATED EQUIPMENT

This section presents the facilities, advanced instrumentation, and digital data acquisition and processing equipment which is available for the hot-rig test program.

Cooled-Turbine High-Temperature Test Facility

The continued emphasis on growth versions of existing engines and better specific power and fuel consumption for new designs establishes the necessity of obtaining high-temperature technology compatible with advanced turbines. Thus, AiResearch has constructed a new cooled-turbine test facility with the following overall objectives:

- o Provide the data necessary to improve or verify the methods used for predicting vane and blade local temperatures for a variety of turbine cooling processes.

- o Provide transient temperature data to allow improvement of methods of predicting vane and blade life.

- o Provide a means of rapidly evaluating the effect of variations in cooling flow rates and modifications to vanes and blades.

- o Provide a means of investigating advanced turbine cooling concepts.

- o Provide a means of investigating the suitability of advanced manufacturing techniques and new materials applicable to experimental and production blades and vanes.

To accomplish these objectives, two rigs are required along with facilities and energies to run them. The test facility layout is shown in Figure A-1, and the primary test operators panel is shown in Figure A-2. The facility is equipped with the latest in instrumentation monitoring, recording, and facility control systems. On-line digital data acquisition with quick-look feedback to the console is provided via three CRT's. This on-line feedback of critical test point data assists the engineers and technicians in operating the rig.

The high-temperature cascade rig, shown in Figure A-3, is used for detailed temperature mapping of turbine vanes and screening tests on various cooling configurations. It is also used for preliminary development of turbine vanes. The cascade rig is capable of operation at 2800°F and 275 psia and is compatible with testing vanes from 0.5 to 3 inches in height.

The high-temperature turbine rotating rig, shown in Figures A-4 and A-5, is used to verify the heat-transfer performance and mechanical integrity of turbine rotor and shroud designs.

A primary design approach used in both rigs was adaptability to a range of turbines, generally between 9 and 18 inches in diameter, and an operating capability up to 2800°F and 250 psia. The rotating rig operating features are indicated in Table A-1.

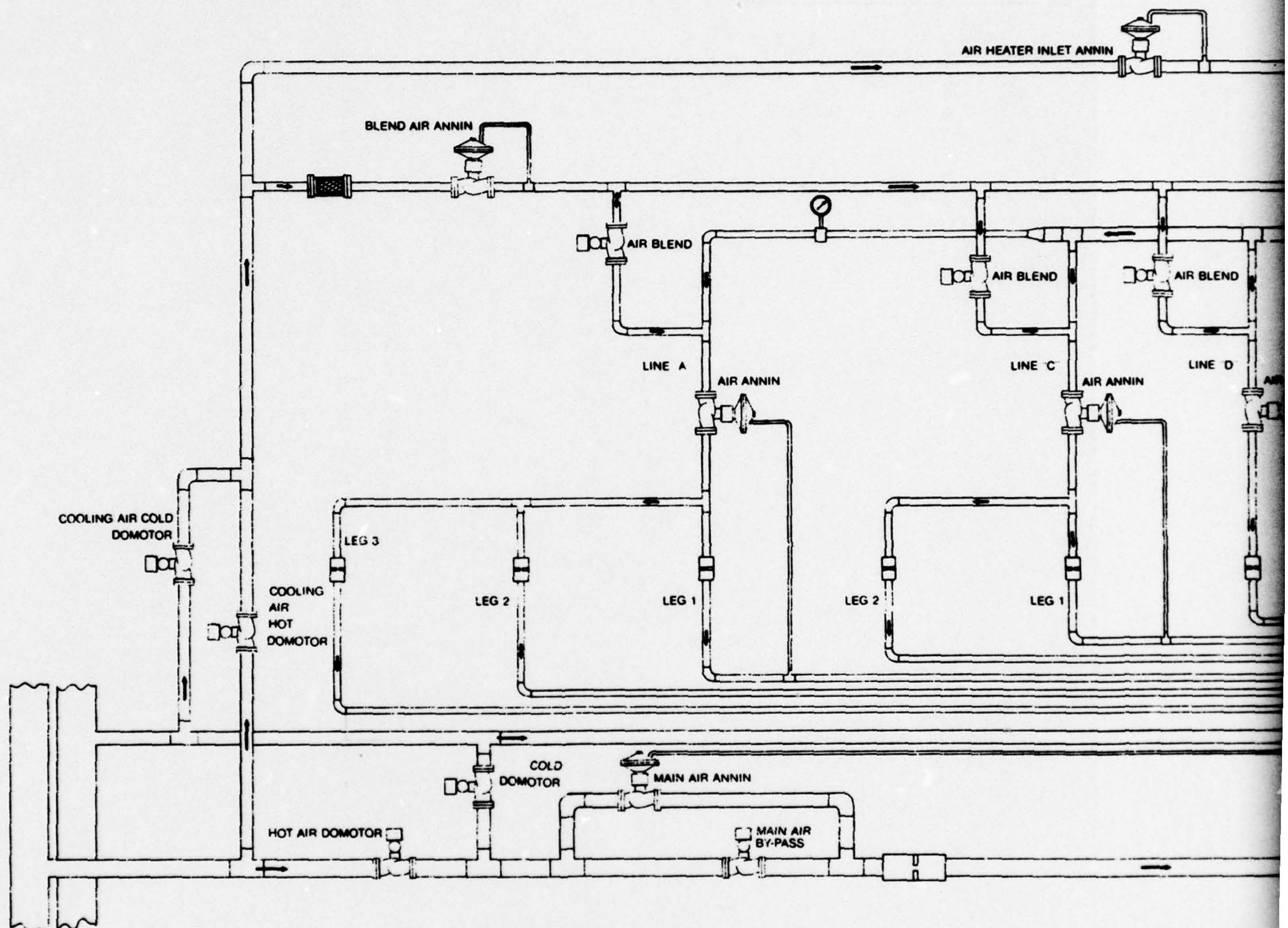
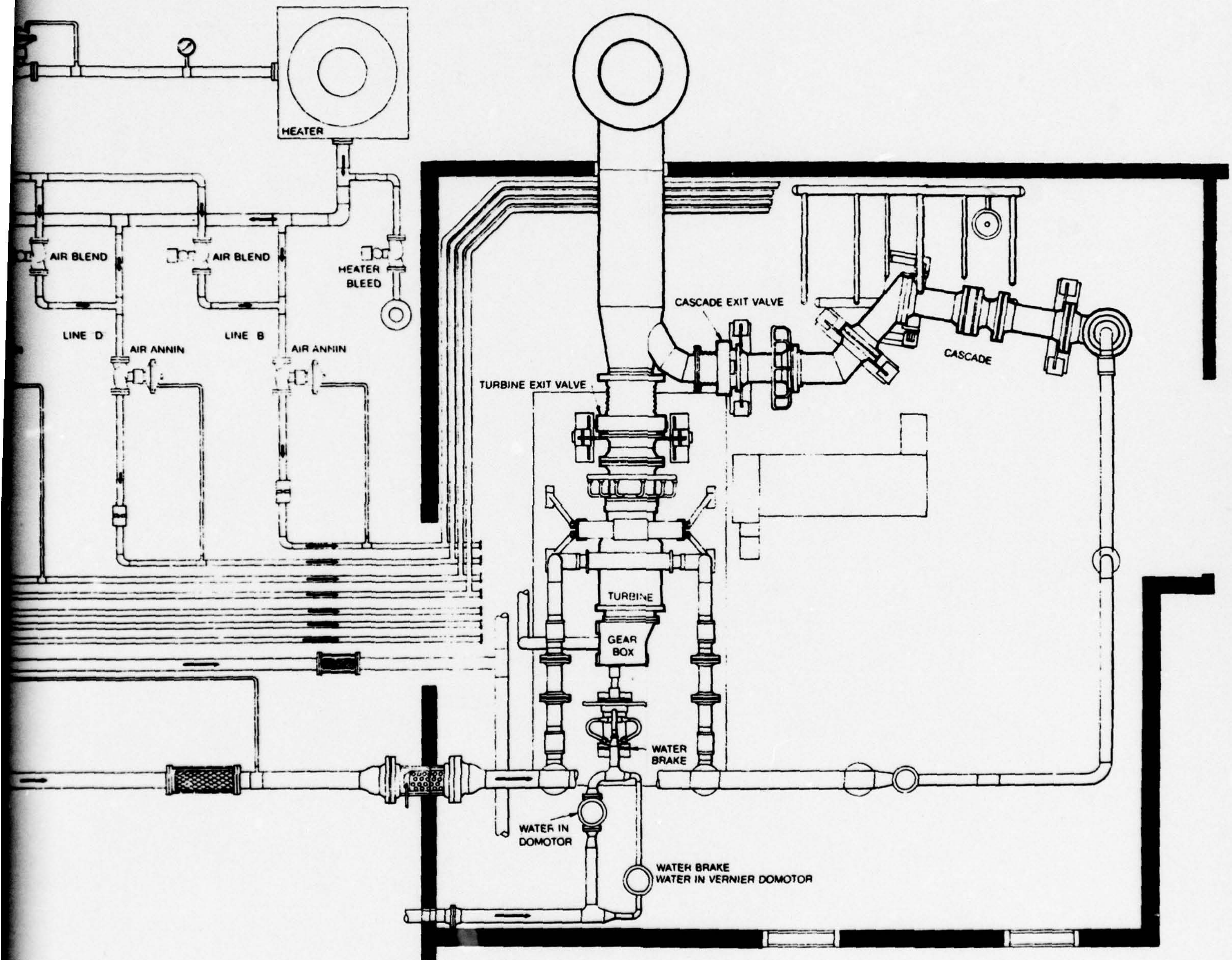


Figure A-1. Cooled T

1



Cooled Turbine Test Facility.

2

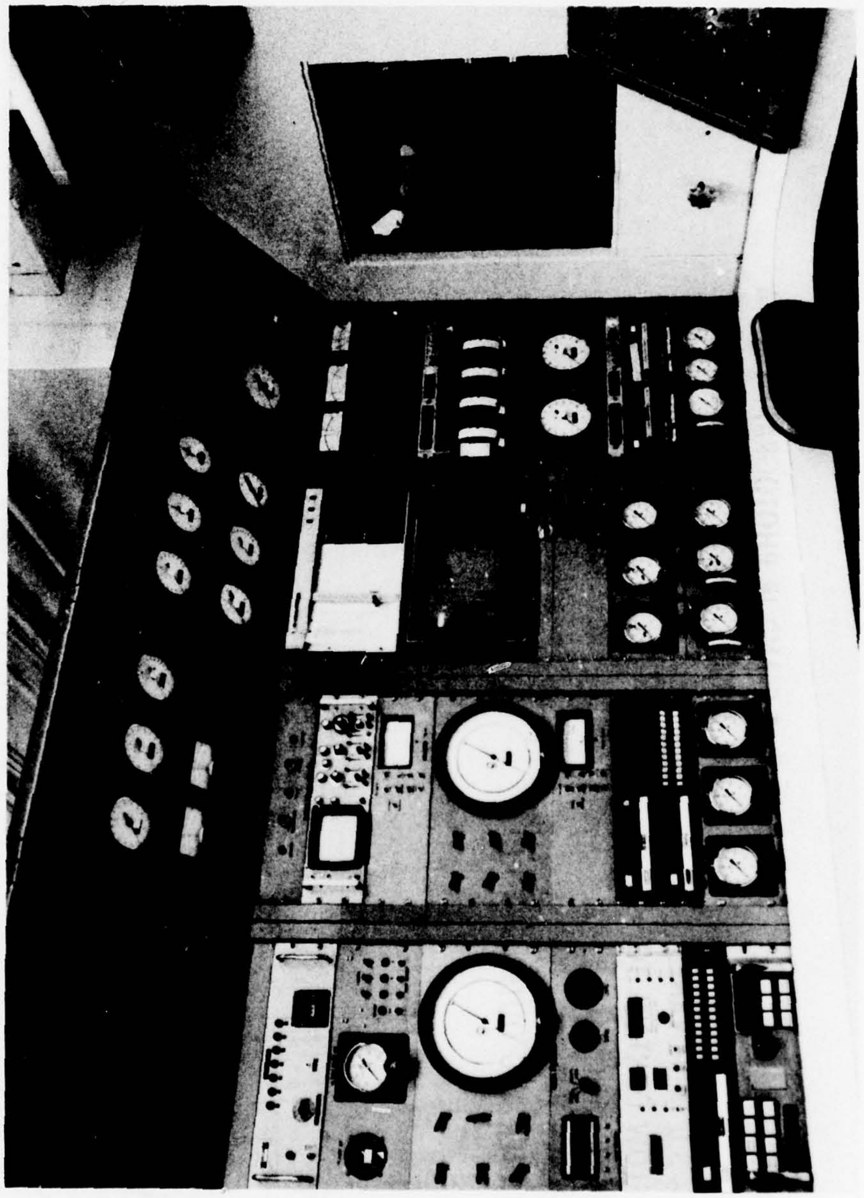


Figure A-2. High-Temperature Turbine Test Panel.

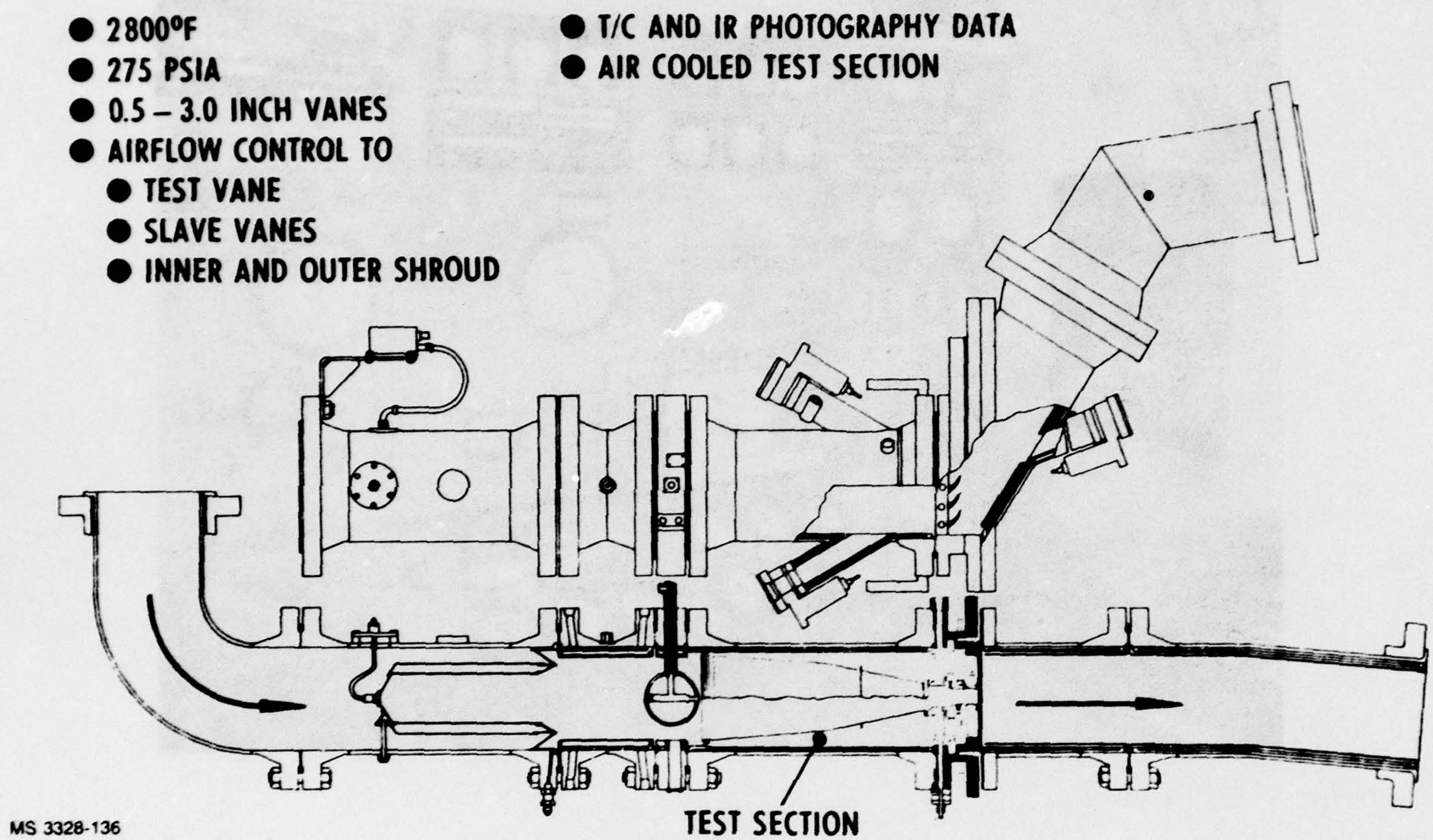


Figure A-3. High-Temperature Turbine Cascade Rig.

731-3 HIGH-TEMPERATURE TURBINE RIG

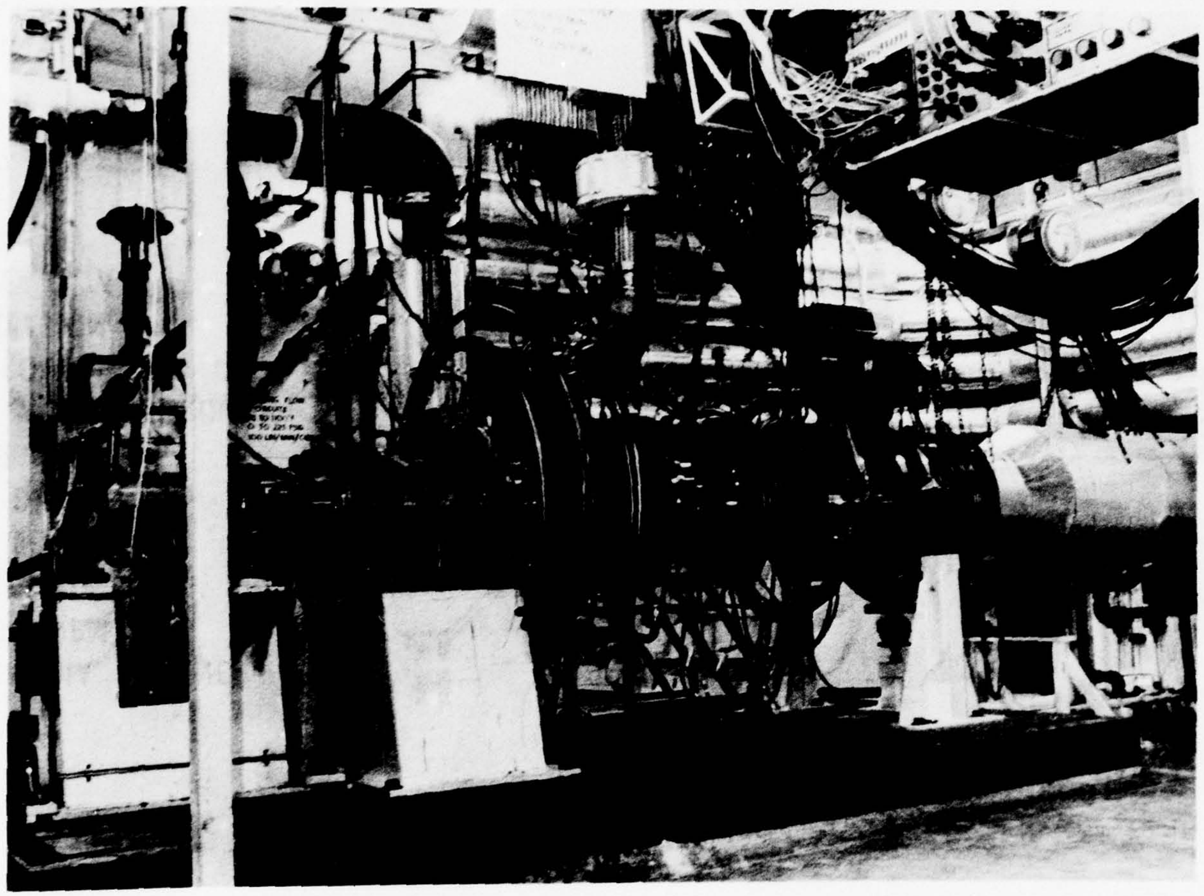
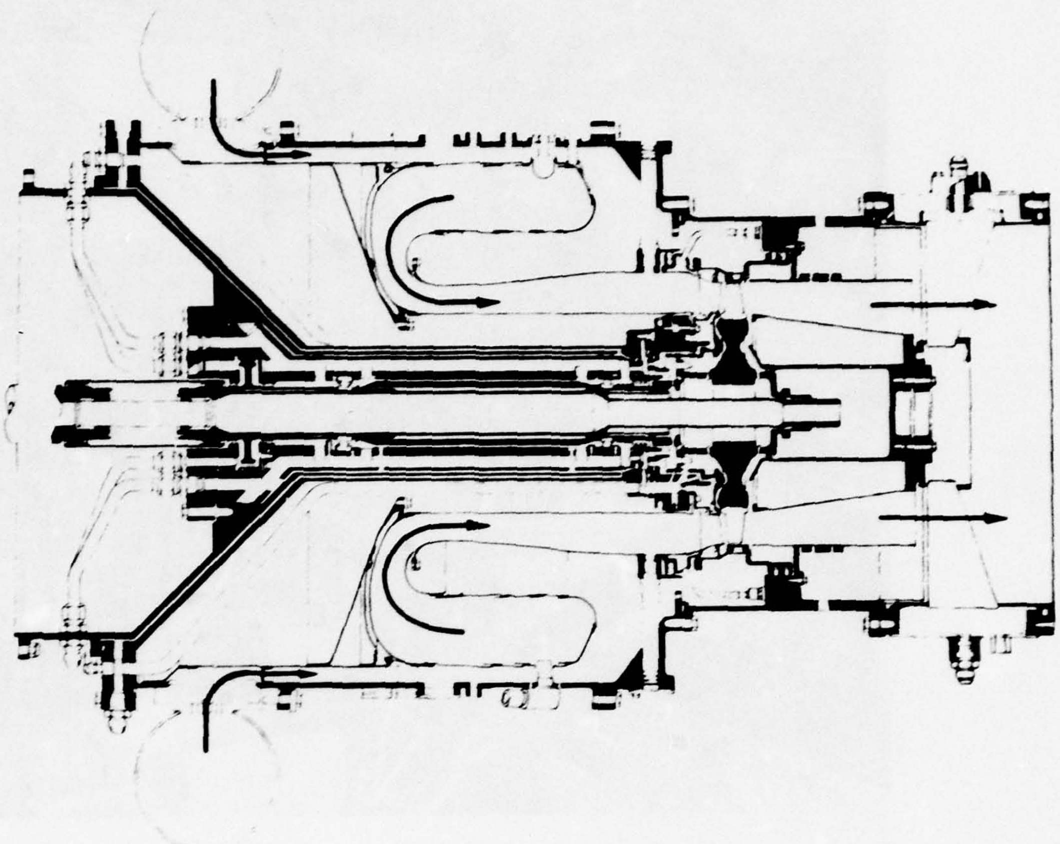


Figure A-4. High-Temperature Turbine Rig.

- 2800°F
- 250 PSIA
- 9 TO 18 IN. DIA. TURBINE
- 0 TO 36,000 RPM
  AIRFLOW CONTROL TO
  - ROTOR BLADES
  - ROTOR DISC
  - STATOR
  - INNER & OUTER SHROUDS
  - TIP SHROUD
- T/C & RADIATION
  PYROMETER DATA



MS 3328-135

Figure A-5. High-Temperature Turbine Rotating Rig.

TABLE A-1. ROTATING RIG FEATURES

(a) 2800°F, 250 psia Capability

(b) 9 to 18 Inch Diameter Turbine

- o ETJ1000 at Reduced Pressure
- o 990 Reduced Flow Design
- o 731 Engine Hardware
- o Referee Turbine

(c) Airflow Control to

- o Rotor Blades
- o Rotor Disk
- o Stator
- o Tip Shroud
- o Inner and Outer Bands

(d) Engine Simulation - Good to Excellent

(e) T/C and Radiation Pyrometer Data

(f) Blade-to-Shroud Clearance Measurement

In general, the measurements made from test rigs will allow predictions of part life and determination of potential problem areas long before they show up in engine testing. The effects of design modifications can be determined immediately on the rigs but not for months in the engine.

Advanced Instrumentation and Instrumentation Laboratory

The Instrumentation Laboratory provides technical and equipment support for the entire AiResearch Phoenix Division. Some of the services and functions it provides are summarized below.

Engineering - To obtain optimum information from testing, advanced instrumentation designs must be utilized. Where such systems are not commercially available, specialized systems must be developed and constructed. Typical of some of these specialized systems are: blade-to-shroud clearance measuring systems for operating gas temperatures up to 2100°F; automatic and manual aerodynamic surveying systems; miniaturized aerothermodynamic probes; miniaturized strain-gauge telemetry system; miniaturized high-speed rotating multiplexer; and high-frequency-response dynamic pressure measuring systems. Advanced instrumentation capability and progress to date are indicated in Figure A-6. Design, fabrication, and installation of instrumentation and programmable process-control facilities are performed as required by product testing to provide measurement and/or control of test parameters and test facilities. Controlled energies include gas and liquid pressure, flow and temperature, speed and position.

Mechanical - The Instrumentation Laboratory incorporates the mechanical skills and equipment needed to ensure support of all research, development, and production activities. Technicians skilled in the use of machine tools, welding, brazing, strain gauging, slip rings, miniaturized work requiring microscopes, etc., provide the required services to ensure successful programs. All special transducers for developmental testing are fabricated by this group. Typical of these are the rotating clearance probe installations shown in Figures A-7 and A-8.

Miniaturized Instrumentation - One of the recent research programs at AiResearch has been to develop high-recovery, miniature total-temperature and total-pressure probes. The design of this instrumentation for measuring temperature and pressure for small turbomachinery poses certain conditions that are somewhat more complex than for equipment of more conventional size.

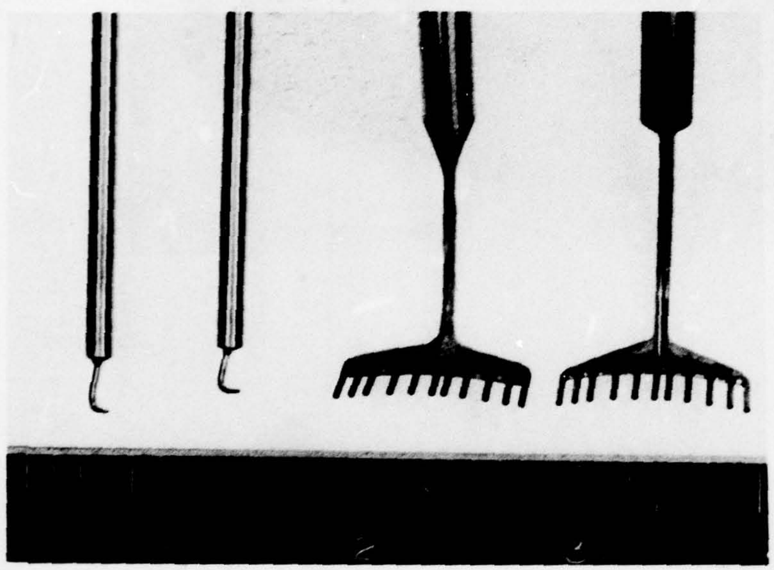
AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

PROGRESS TO DATE

- MINIATURE THERMOCOUPLE
- PRESSURE PROBE
- ROTATING T/C MULTIPLEXER
- INFRARED PHOTOGRAPH
- RADIATION PYROMETER
- HIGH TEMPERATURE TRAVERSE PROBES
- FLUSH SKIN TEMPERATURES
- HIGH TEMPERATURE CLEARANCE PROBE

FUTURE REQUIREMENTS

- ROTATING PRESSURE MULTIPLEXER
- RADIATION PYROMETER
- TURBULENCE METER
- PLASMA SPRAY EQUIPMENT



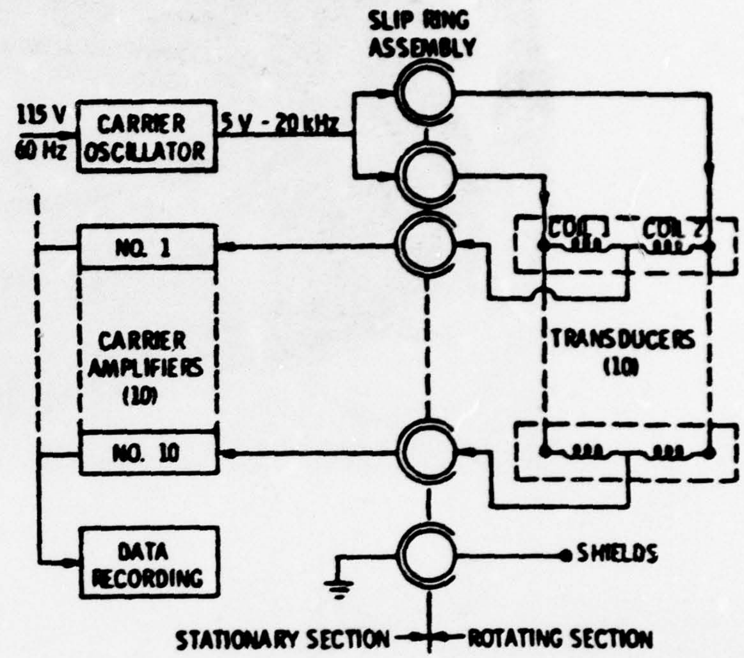


Figure A-6. Instrumentation Capability

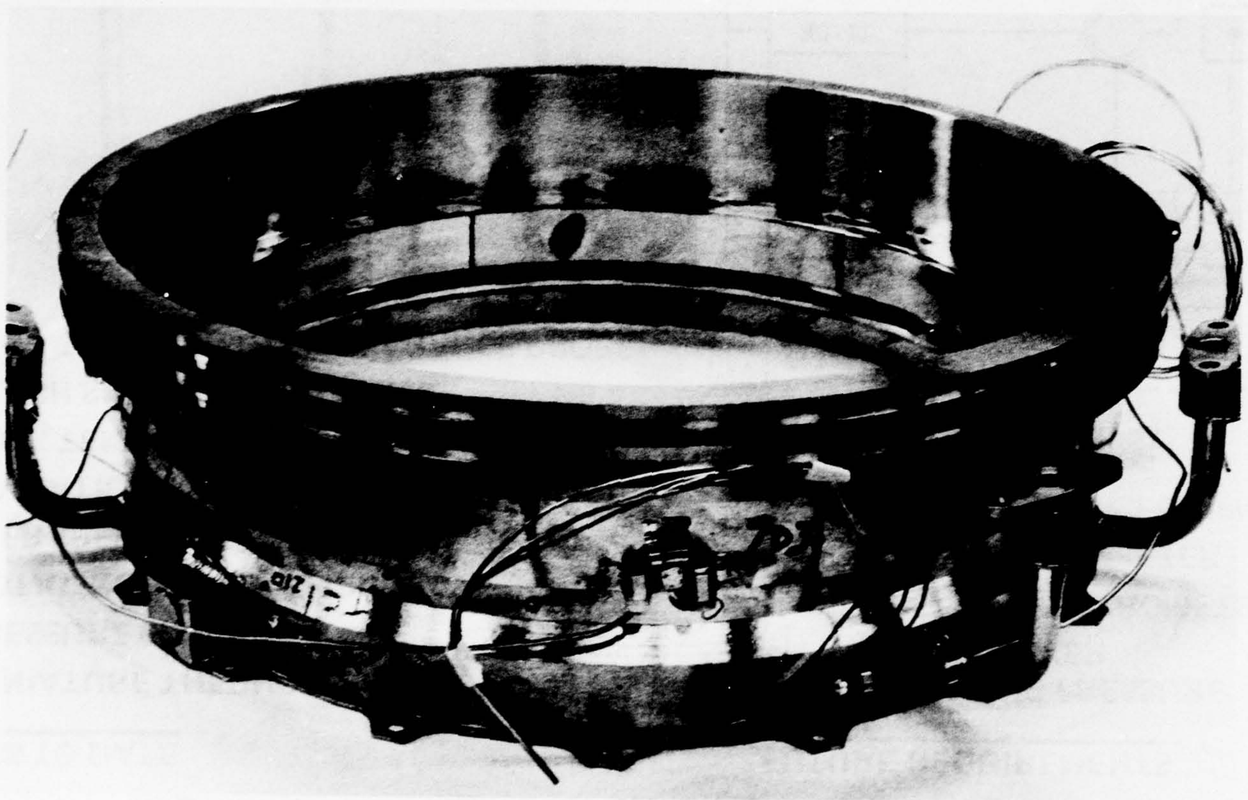


Figure A-7. High-Temperature Clearance Probe Installation.

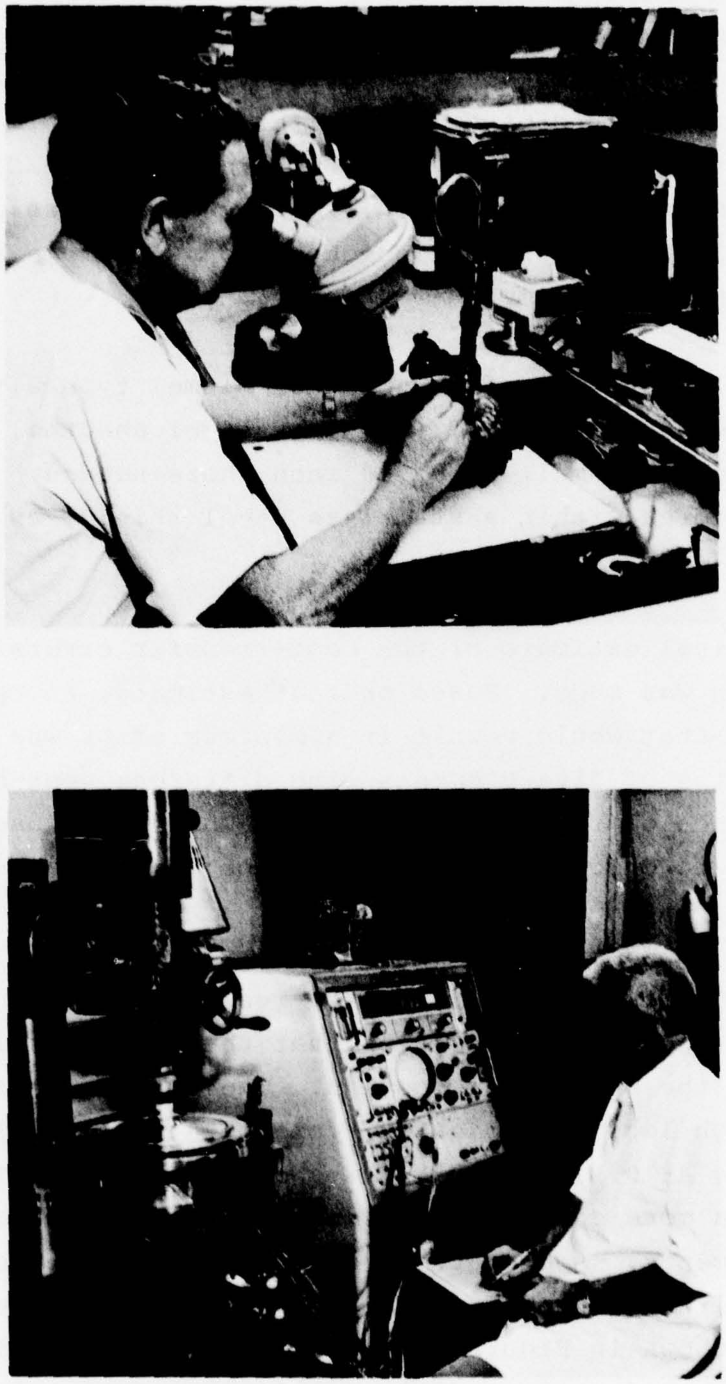


Figure A-8. Measuring Rotating Group Clearances with Custom-Fabricated Distance Probes.

Stream blockage, which is always one of the main factors in deciding the size and number of probes to be used at a certain location, becomes even more important as turbomachinery becomes smaller. On the other hand, it is not a simple case of "the smaller, the better" because the thermocouple (T/C) shield bleed holes and even the sensor inlet holes themselves are quite susceptible to plugging or foreign-object damage from vapors and particles in the airstream.

The T/C elements are of the Chromel-Alumel type with magnesium-oxide insulation and stainless steel sheaths, having outside diameters as small as 0.010 inch where needed. The T/C element is centered within a stainless steel shield, as shown in Figures A-9 and A-10.

An analytical estimate of the heat-transfer errors for the miniature T/C's was made. Based on that estimate, an optimum vent hole size that would result in a minimum error was chosen. A rake consisting of five elements with different vent-hole sizes was made for each of two T/C wire sizes. These were used in a test conducted to check the recovery factor versus Mach-number variation with vent-hole size.

Figure A-9 shows the variation of recovery with vent-hole size for 0.020 MgO. It can be seen that the data correlates favorably with the analytical results. The same results were achieved (though less dramatically) for the 0.010-inch T/C as shown in Figure A-10. Figure A-11 shows the miniature T/C rakes, together with a more conventional size rake consisting of three 0.125-inch elements. A high temperature radial traverse actuator equipped with Platinum Rhodium thermocouples has been developed, as shown in Figure A-12, to measure turbine inlet gas temperatures and their radial profile in a semi-automatic digital system.

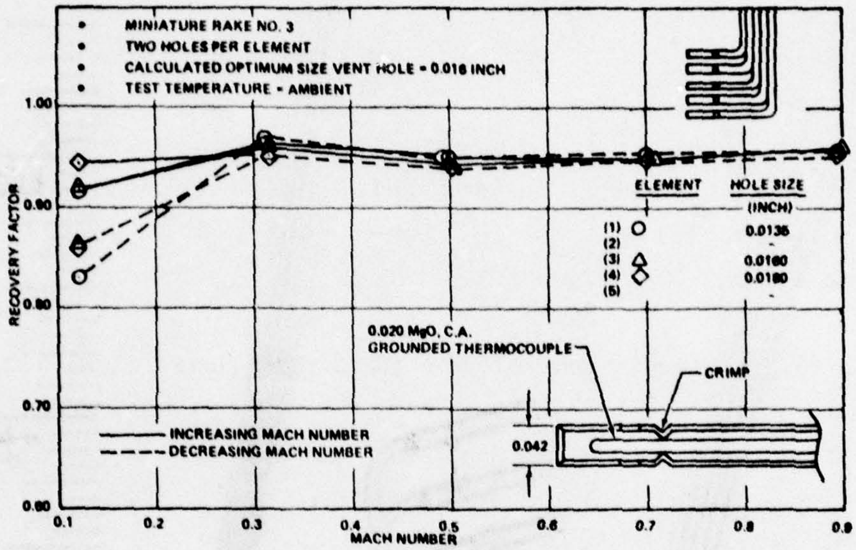


Figure A-9. Miniature (0.020-Inch) Thermocouple Study of Recovery Factor for Various Vent-Hole Sizes.

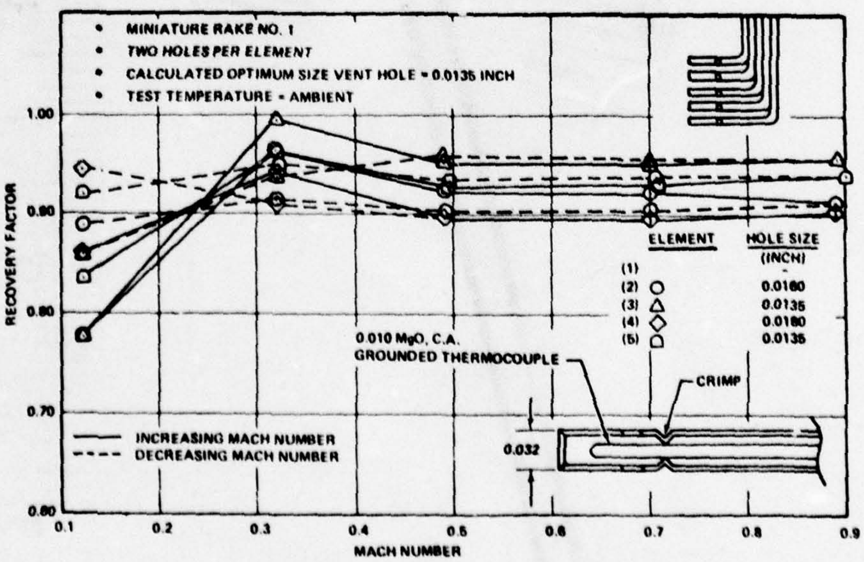
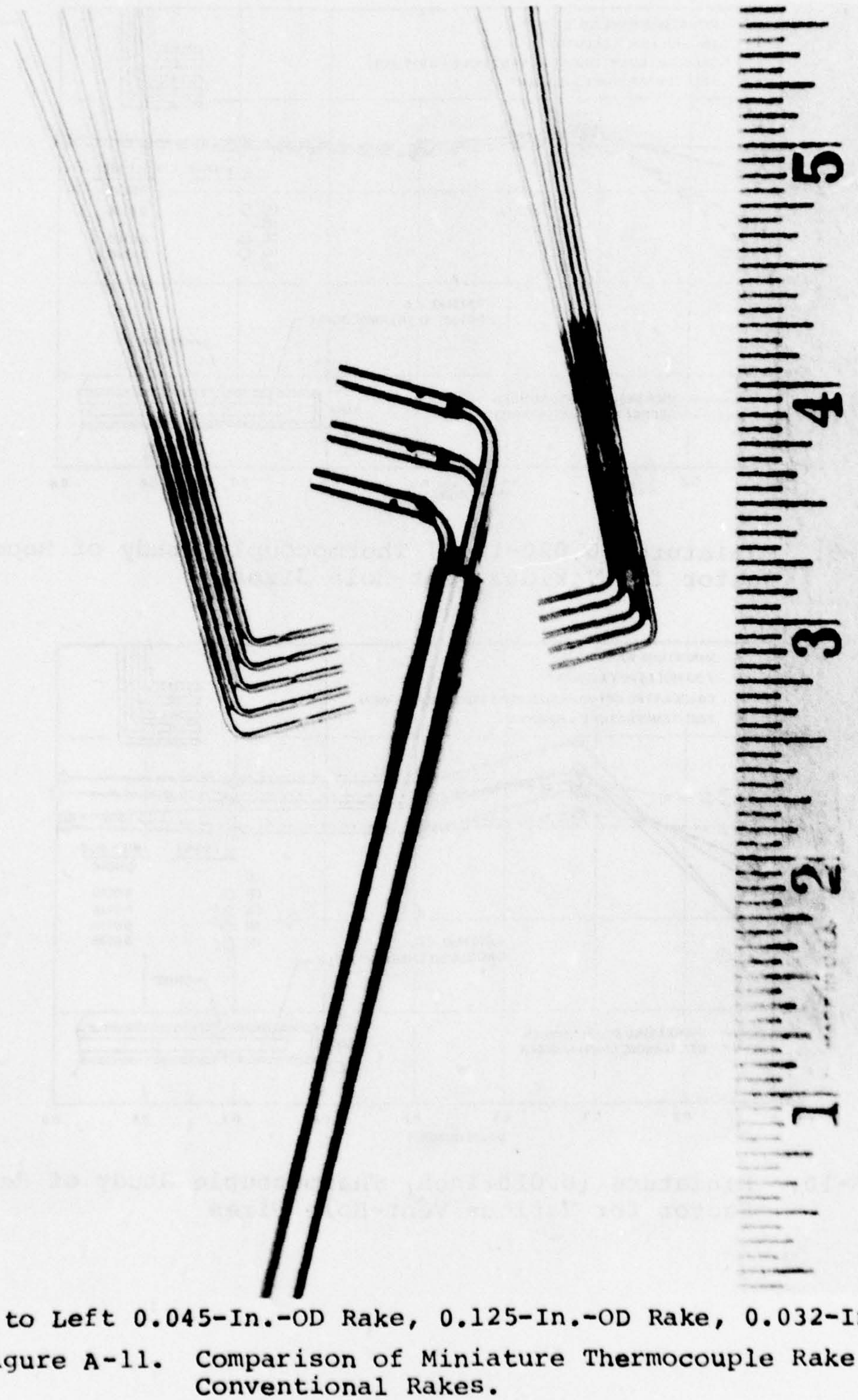


Figure A-10. Miniature (0.010-Inch) Thermocouple Study of Recovery Factor for Various Vent-Hole Sizes



Right to Left 0.045-In.-OD Rake, 0.125-In.-OD Rake, 0.032-In.-OD Rake.

Figure A-11. Comparison of Miniature Thermocouple Rake with Conventional Rakes.

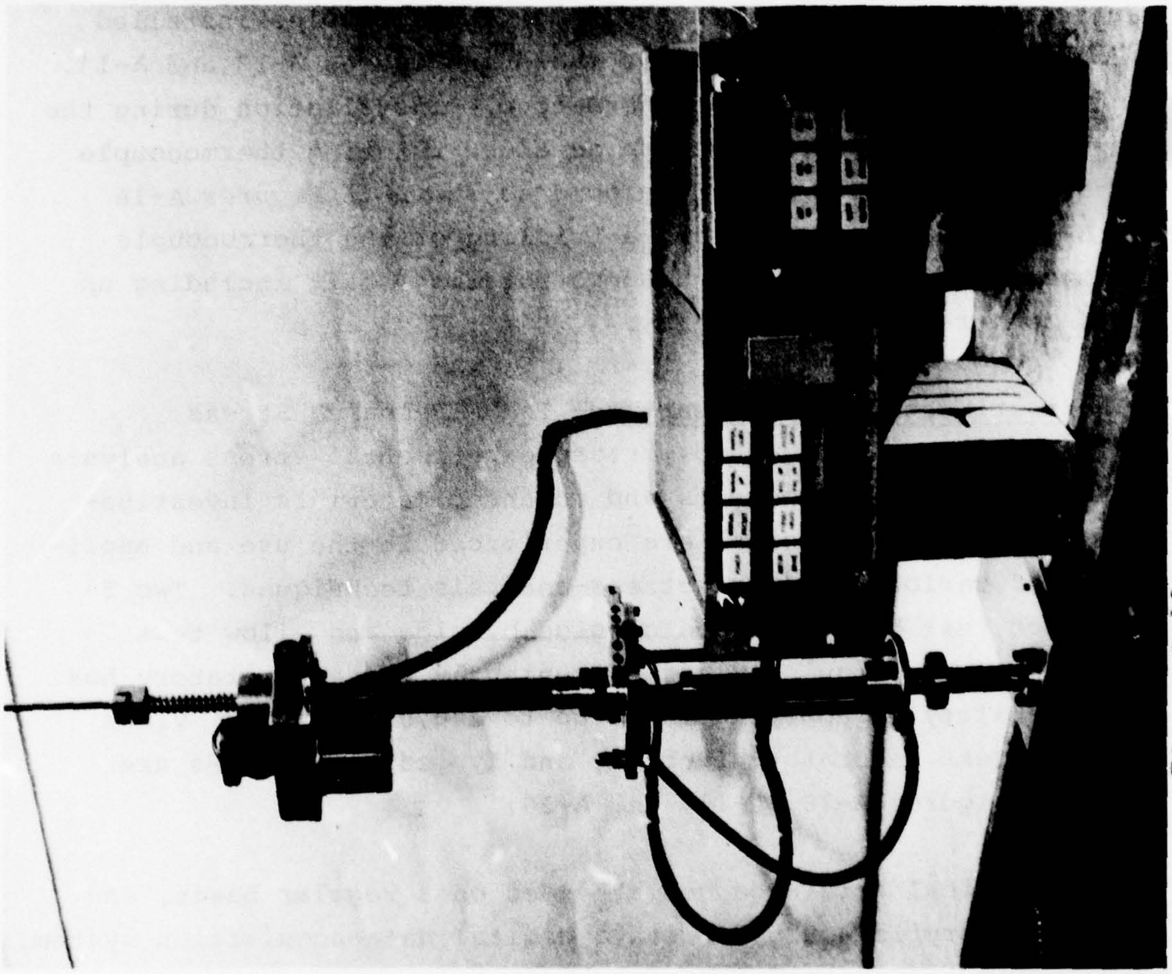


Figure A-12. High-Temperature Traverse.

In turbomachinery, access to the various parts to be instrumented can be rather difficult. AiResearch in its high temperature turbine testing has had experience with this type of instrumentation in the present TFE731-3 axial turbine installation. A method of installing thermocouples in the surface of small cooled blades and vanes has been developed. The flush surface installation techniques permit accurate metal temperature measurements, and the couples do not change either the heat transfer rates or pressure gradients around the blades. The turbine rotor assembly with 0.010 MgO thermocouples installed flush in the blades and disk is shown in Figures A-13 and A-14. Figure A-15 shows the blade thermocouple installation during the plasma spray process. Also, an advanced rotating thermocouple multiplex system has been developed as shown in Figures A-16 and A-17. This system allows a tripling of the thermocouple readout capacity from a high speed rotating shaft including up to 44 temperature measurements.

Experimental Stress Testing - The AiResearch Stress Facility was established to perform experimental stress analysis of turbine engine components and advanced materials investigations. The test personnel are experienced in the use and application of various types of stress-analysis techniques. Two 5- by 7-foot test beds are located side by side and allow test setups to be made quickly and conveniently. The Laboratory has the capability of applying loads up to 200,000 pounds. Views of the Stress Laboratory facility and typical activities are shown in Figures A-18, A-19, and A-20.

Electrical strain gauges are used on a regular basis, and the Laboratory is equipped with a digital data-acquisition system. This system can signal condition, scan print, and punch a tape for computer input for strain gauges, load cells, pressure transducers, position indicators, and many other types of instrumentation. It allows many data points to be monitored quickly and

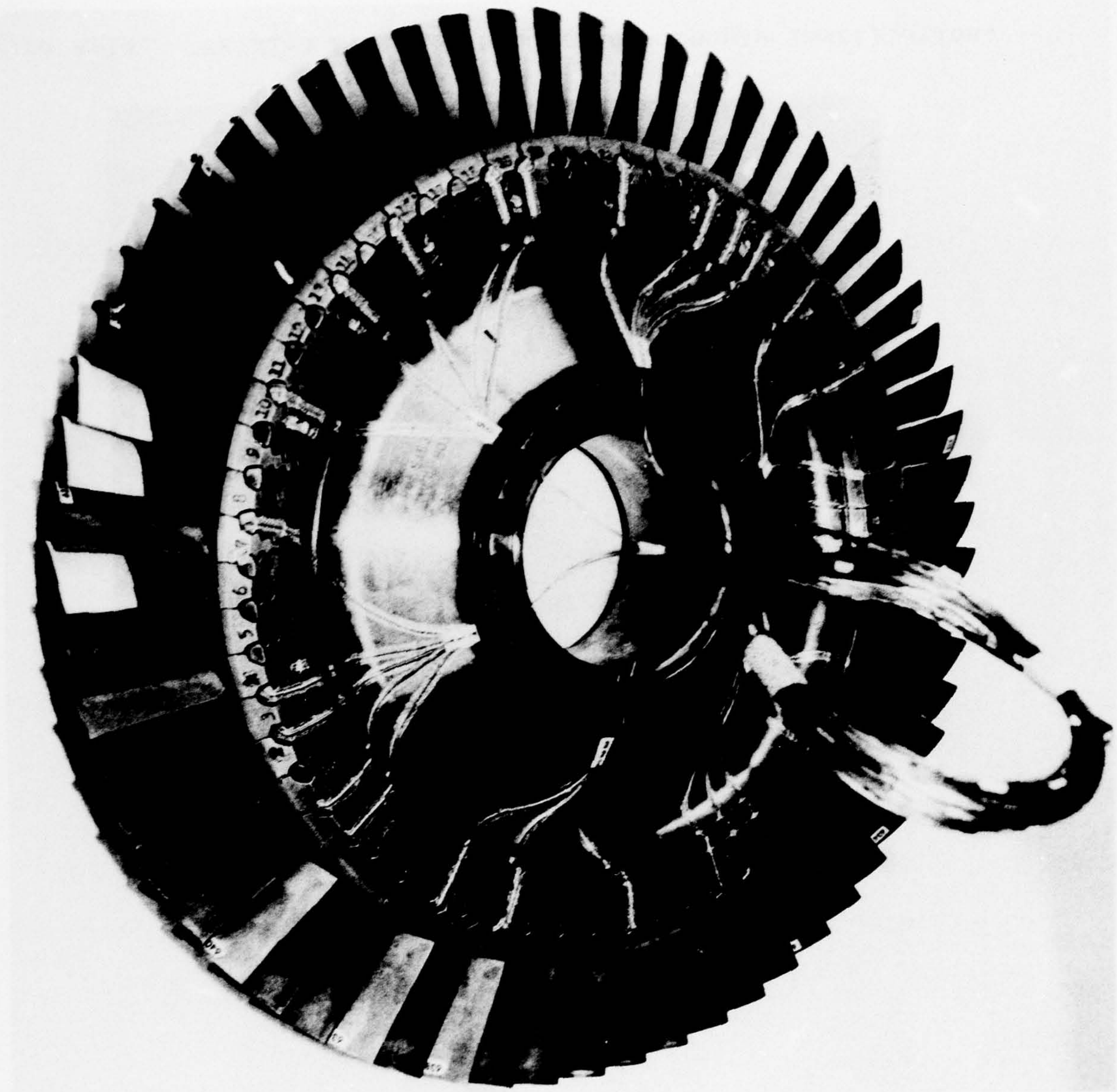


Figure A-13. Instrumented Cooled Turbine Rotor.

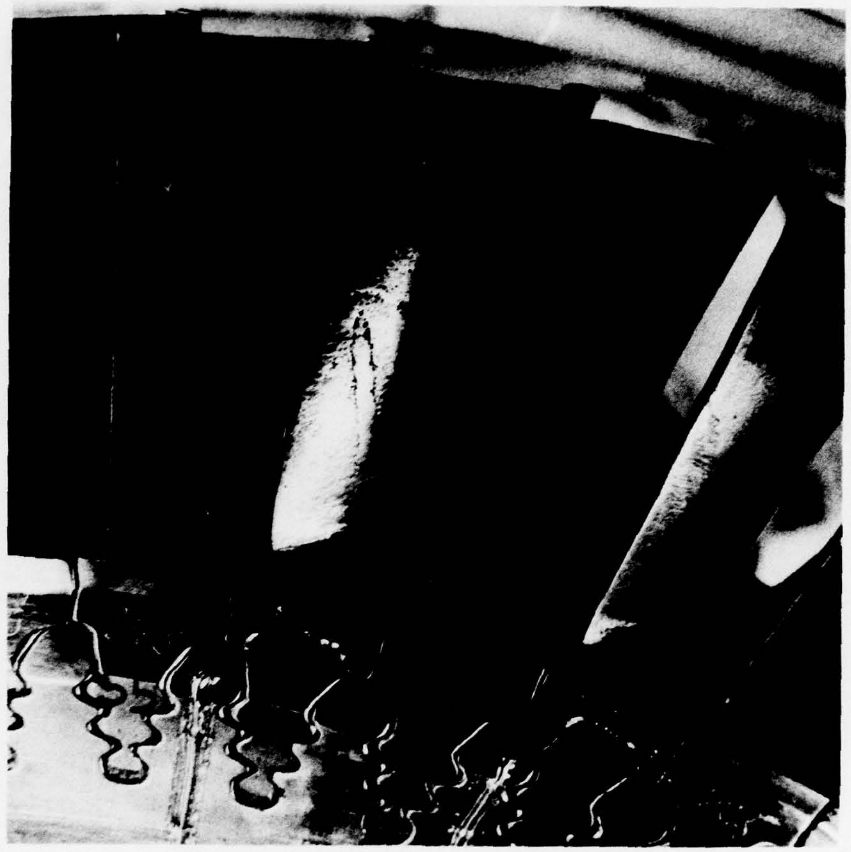


Figure A-14. TFE731-3 Finished Blade Thermocouple Installation.

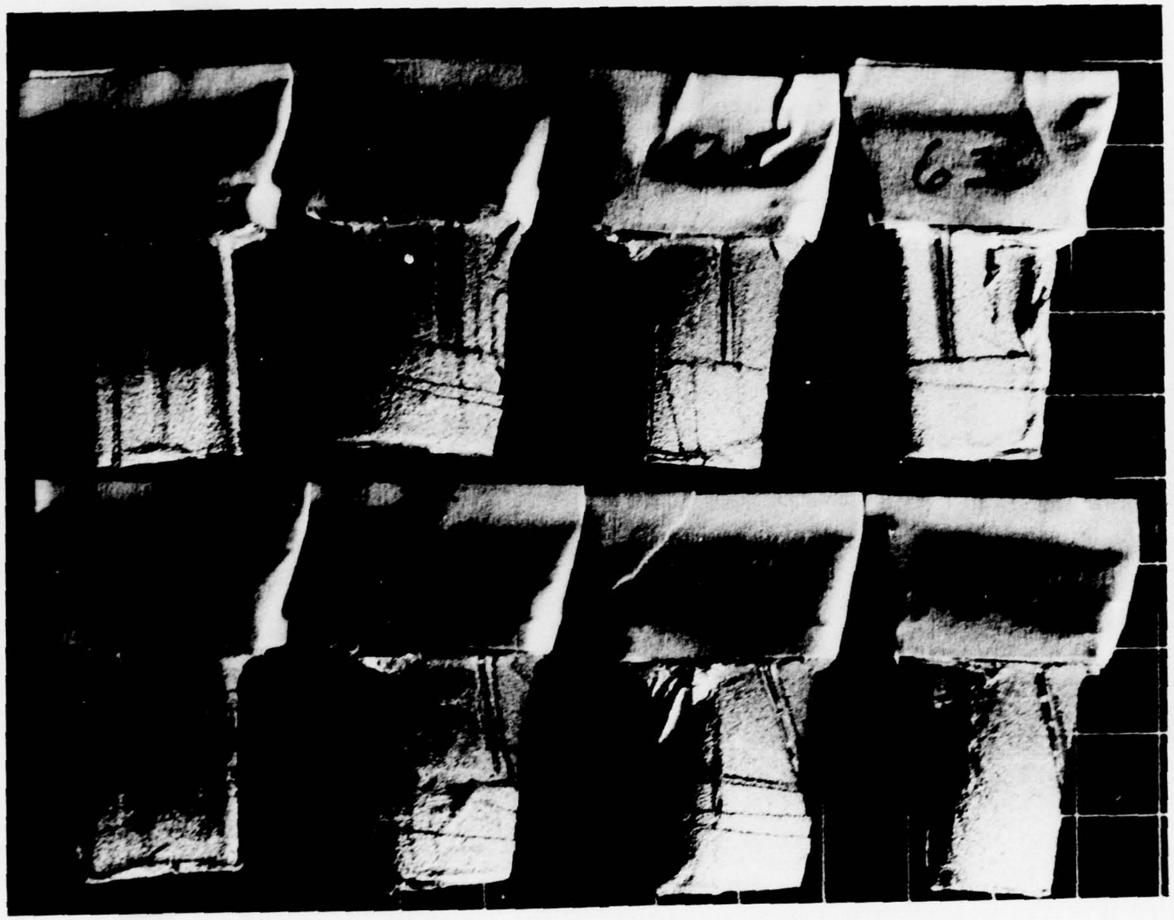


Figure A-15. Blade Thermocouple Installation During Plasma-Spray Process.

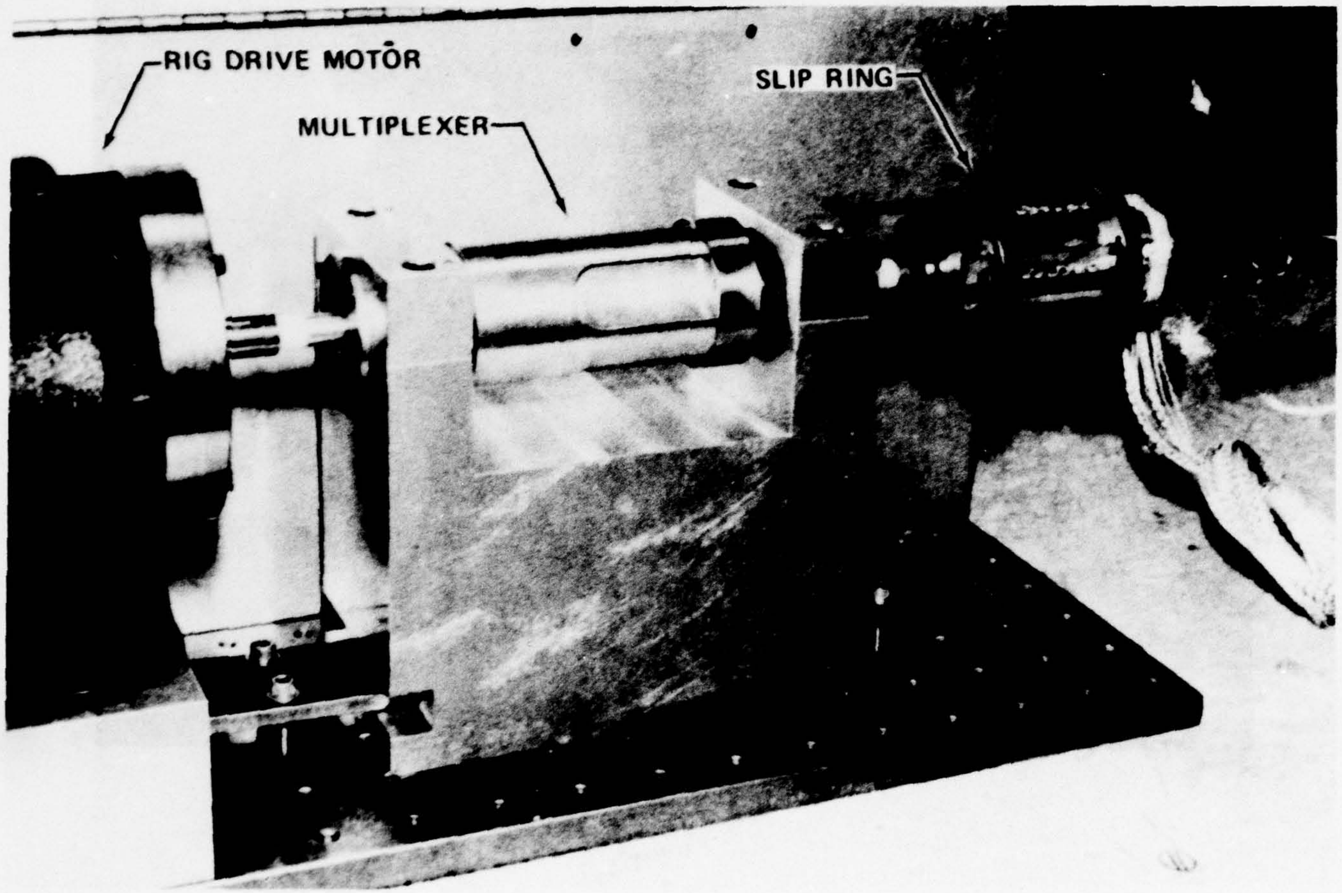


Figure A-16. Prototype Rotating Thermocouple Multiplexer System.

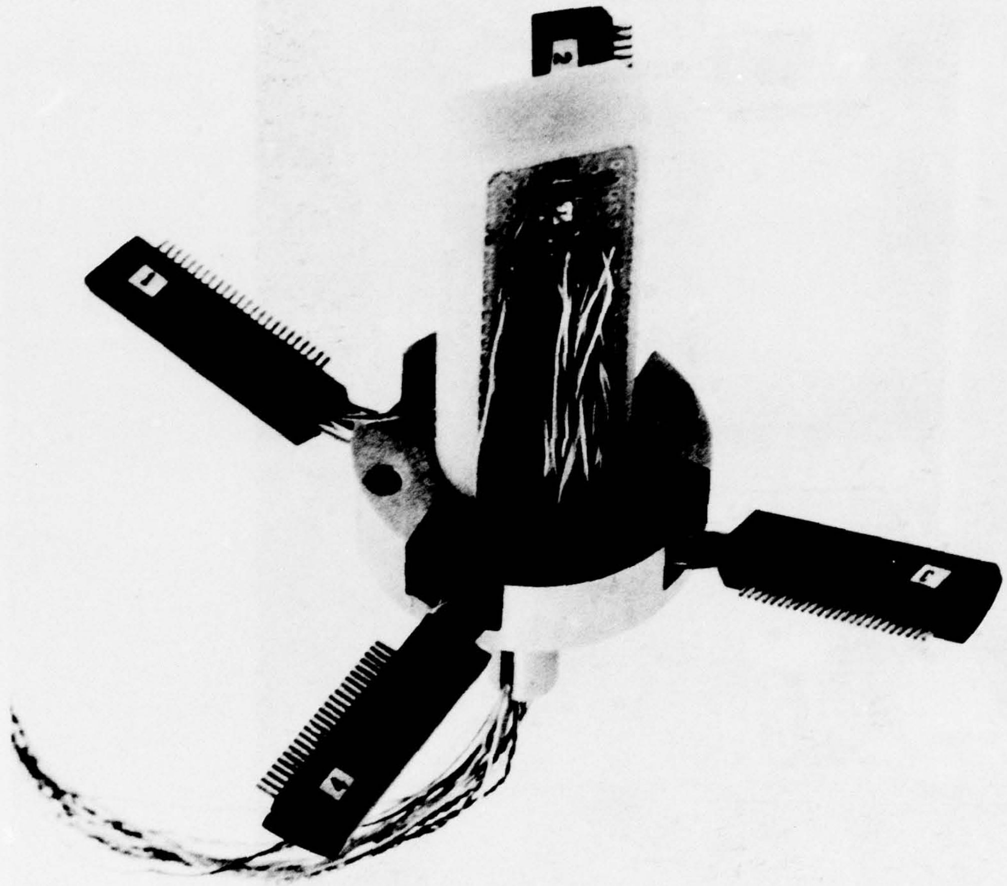


Figure A-17. Rotating Thermocouple Multiplexer.

Figure A-18. Stress Laboratory Facility.

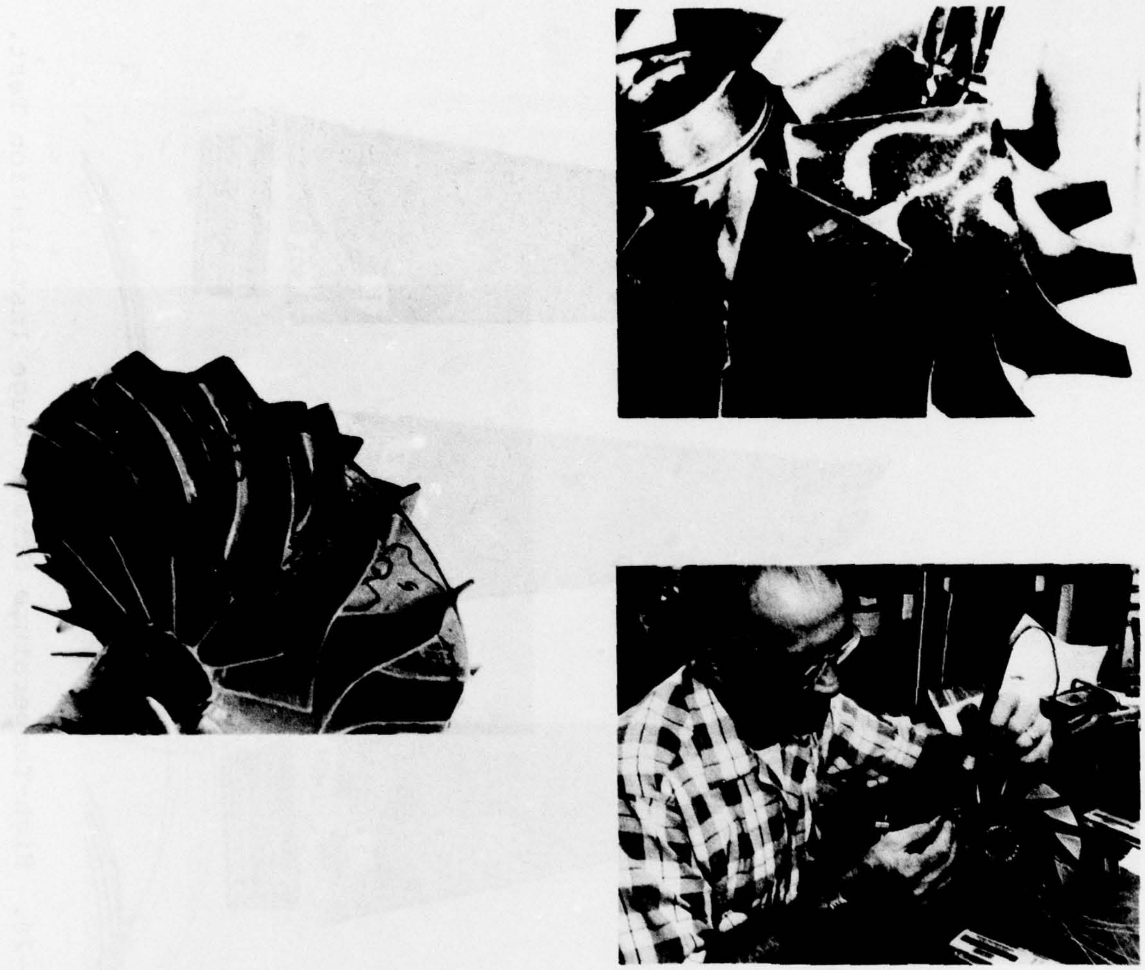


Figure A-19. Mechanical-Integrity Inspection.

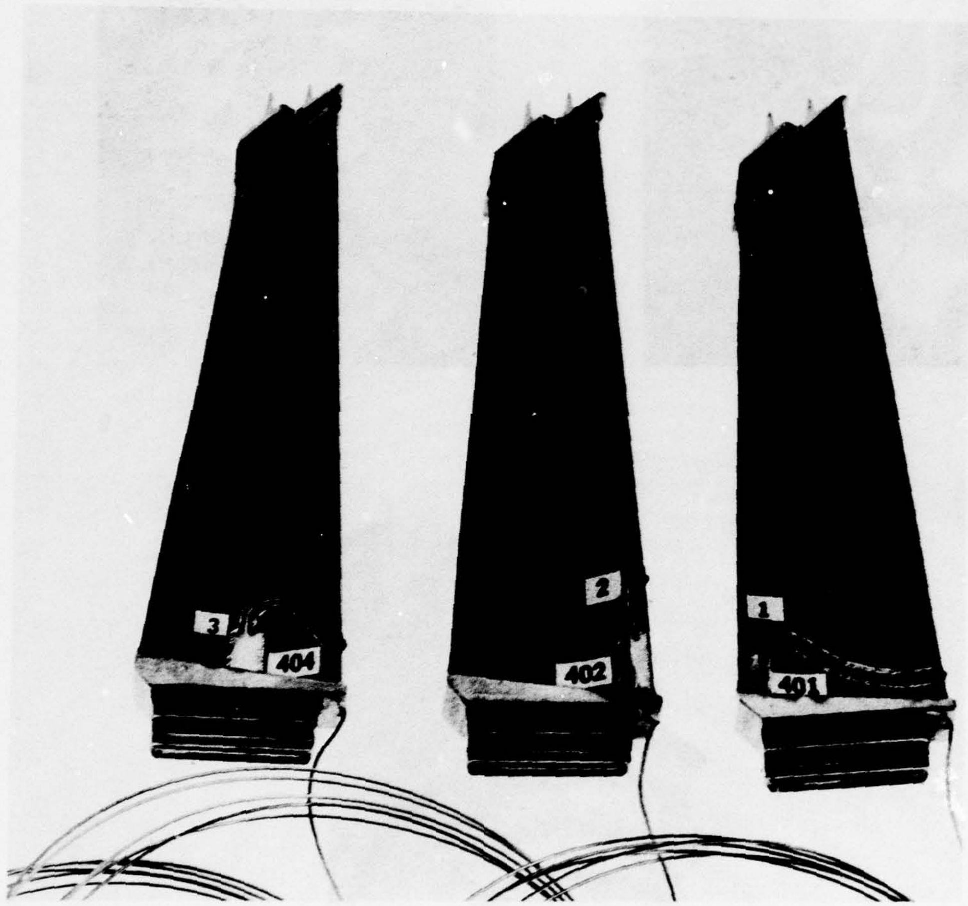


Figure A-20. High-Temperature Strain Gauge Installation Test.

accurately. Actual engine hardware may be tested with use of these methods, or photoelastic and scale models may be tested. Brittle coatings such as Stresscoat are used under moderate temperatures, while Stresscoat All-Temp is used at elevated temperatures and/or contaminated atmospheres.

Dynamic measurements of test parameters are performed with oscillographs, magnetic tape recorders, strip chart recorders, X-Y plotters, oscilloscopes, real-time analyzers, and special scopes. Fourier analyses are conducted on strain, sound, and other signals. A typical analog recording area is shown in Figure A-21.

Digital Data Acquisition and Processing

AiResearch maintains a wide selection of digital data-acquisition systems for servicing all of the test facilities, remote sites, and flight tests. These systems are classified into three categories:

- Punched paper tape output
- Magnetic tape output
- Complete calculated and plotted data

A staff of qualified programmers, engineers, and technicians is available to operate and maintain these systems. Two fully computerized data-acquisition systems are provided. One of these systems consists of a Systems Engineering Laboratories Model 810A. This unit is mounted in a trailer, along with its peripheral equipment, making it a fully mobile system. It is used to service the remote test facilities and testing at other facilities where digital capabilities are required and not otherwise available. The system has the capability of data acquisition at a rate of 200 samples per second. This data can be converted into engineering units and displayed on a KSR35 teletype

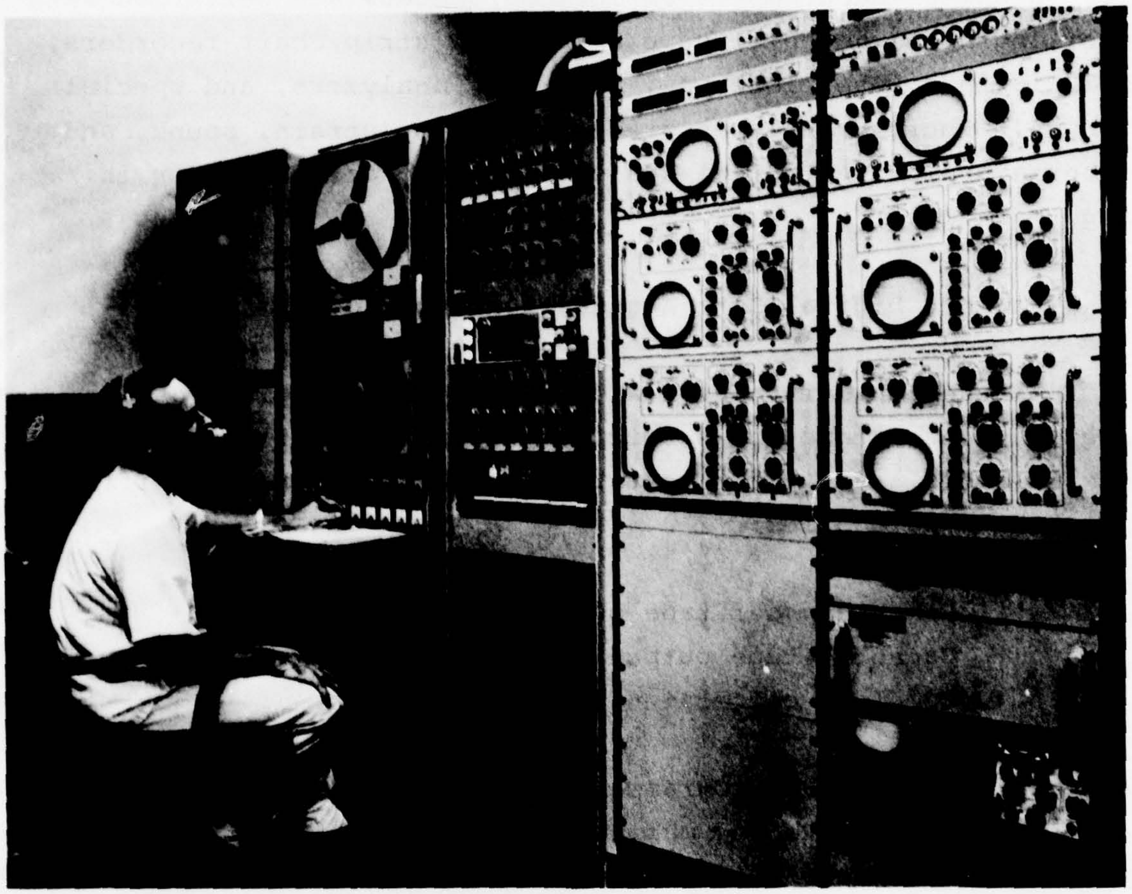


Figure A-21. Analog Recording Facility.

or CRT. Alarm capabilities for up to 16 parameters are possible on real-time conditions. The hardware and software of the system are fully compatible with the central computerized data-acquisition system. This interchangeability permits maximum flexibility, economy, and rapid turnaround of data.

The computerized data-acquisition system, as shown in Figure A-22, services all of the Laboratory facilities. It consists of a Systems Engineering Laboratories Model 810B computer with 32,000 words of memroy. Its peripheral equipment consists of a 400-card-per-minute card reader, 600-line-per-minute printer, Gould 5000 printer-plotter, ASR33 teletype, eight CRT's, three magnetic tape recorders, two disc storage units (one movable head and one fixed head), and five remote, portable multiplexers. The multiplexers can be located anywhere within the facilities where required. Communication between the computer and its remote multiplexers is achieved through a network of coaxial cables used as serial transmission links. Where cables are not possible, an infrared link is used.

Simultaneous data is acquired at the rate of 200 samples per second from any of four multiplexer test locations. With special equipment, sampling rates may go as high as 250,000 samples per second. Data is recorded on magnetic tape for permanent storage. On-line data output coupled with quick-look capabilities of selected performance calculations is available. This data is displayed at the test site by means of CRT systems. A typical CRT display is shown in Figure A-23. Complete data logging in engineering units, performance calculations, and plots are available within seconds of test completion.

Figure A-22. Computerized Data Acquisition Center.

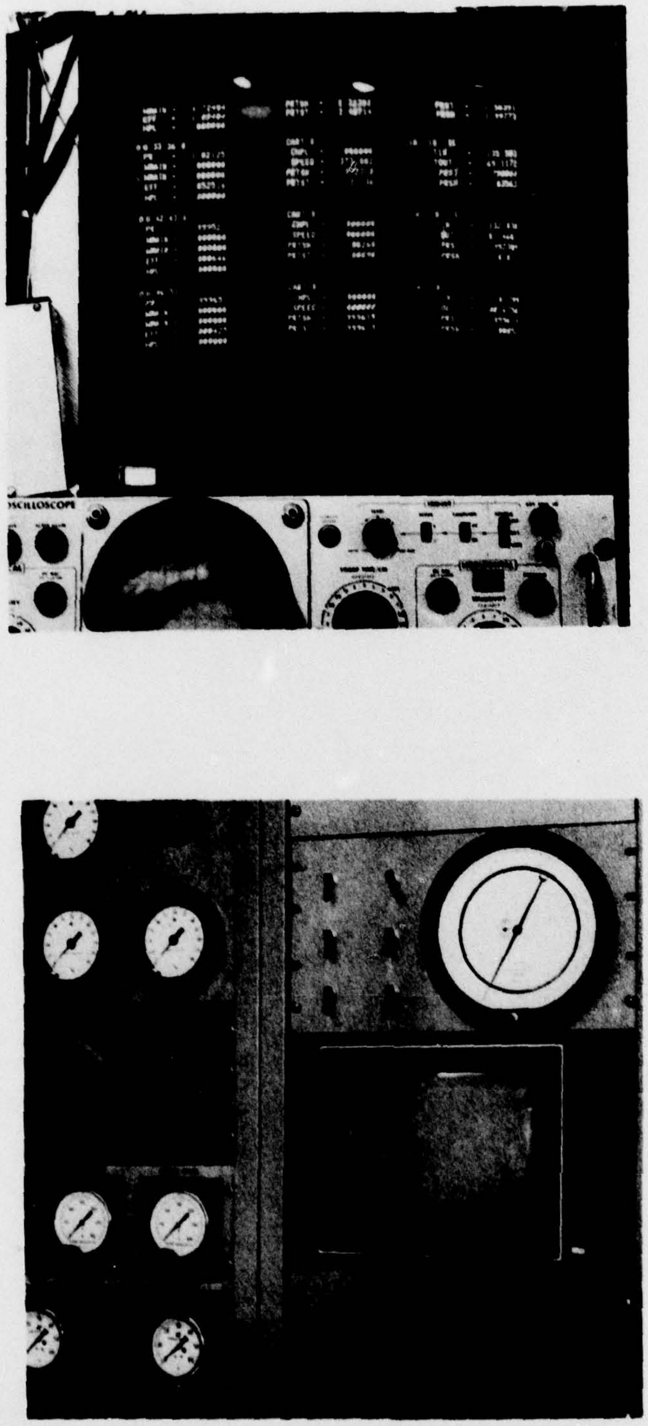


Figure A-23. Typical CRT Data Display Units.

*U.S.Government Printing Office: 1978 — 657-002/156